ERDA—76/110/2

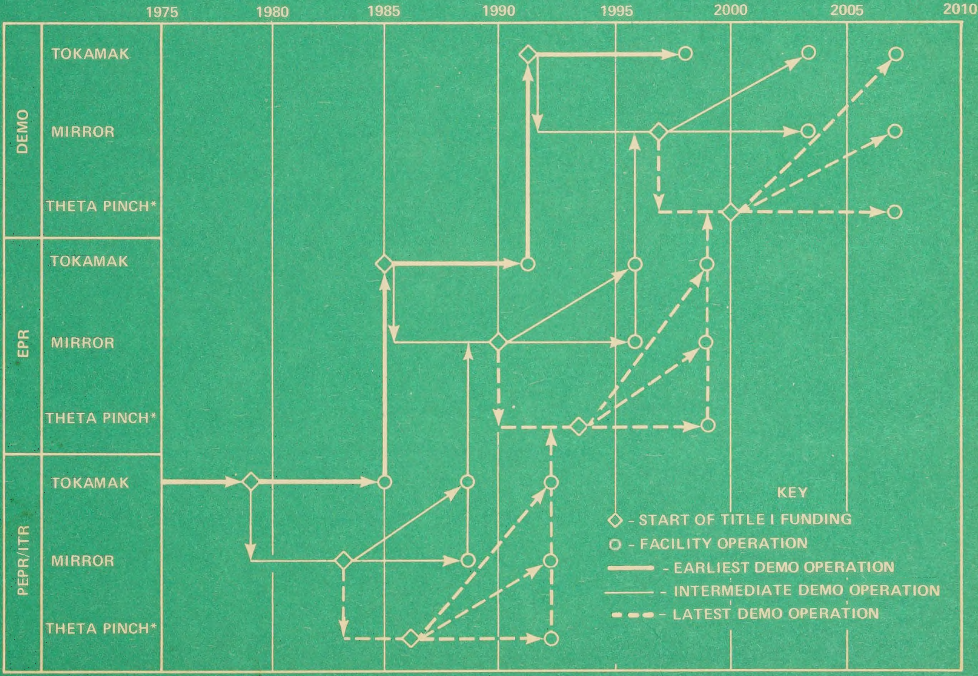
Fusion Power By Magnetic Confinement Program Plan

Energy Research & Development Administration
Division Of Magnetic Fusion Energy

July 1976

Volume II
Long Range Planning Projections

LOGIC III REFERENCE OPTION PROGRAM PATH ALTERNATIVES



* OTHER ALTERNATE CONCEPTS WOULD FOLLOW THE THETA PINCH PATH

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FUSION POWER BY MAGNETIC CONFINEMENT

PROGRAM PLAN

VOLUME II

LONG RANGE PLANNING PROJECTIONS

JULY 1976

Prepared by the
Division of Magnetic Fusion Energy
U.S. Energy Research and Development Administration

Abstract

The Fusion Power Program Plan treats the technical, schedular and budgetary projections for the development of fusion power using magnetic confinement. It was prepared on the basis of current technical status and program perspective. A broad overview of the probable facilities requirements and optional possible technical paths to a demonstration reactor is presented, as well as a more detailed plan for the R&D program for the next five years. The "plan" is not a roadmap to be followed blindly to the end goal. Rather it is a tool of management, a dynamic and living document which will change and evolve as scientific, engineering/technology and commercial/economic/environmental analyses and progress proceeds. The use of plans such as this one in technically complex development programs requires judgment and flexibility as new insights into the nature of the task evolve.

The presently-established program goal of the fusion program is to DEVELOP AND DEMONSTRATE PURE FUSION CENTRAL ELECTRIC POWER STATIONS FOR COMMERCIAL APPLICATIONS. Actual commercialization of fusion reactors will occur through a developing fusion vendor industry working with Government, national laboratories and the electric utilities. Short term objectives of the program center around establishing the technical feasibility of the more promising concepts which could best lead to commercial power systems. Key to success in this effort is a cooperative effort in the R&D phase among Government, national laboratories, utilities and industry.

There exist potential applications of fusion systems other than central station electric plants. These include direct production of hydrogen gas and/or synthetic fuels; direct energy production for chemical processing; fissile fuel production; fission product waste disposal; and fusion-fission hybrid reactors. Efforts are in progress to evaluate these applications; the present and planned programs will permit timely information on which decisions can be made to pursue these goals.

The pace of the fusion program is determined by both policy variables and technical variables. A multiplicity of plans, referred to as Program Logics, are outlined. These range from "level of effort research" to "maximum effective effort" and are primarily describable by the presumed level of funding. Within these program logics there are many optional technical paths. A few of the potential paths or options are outlined.

The tokamak is currently the most promising approach to fusion and is closer to achieving a demonstration reactor for commercial application than other fusion concepts; but active programs in other concepts are pursued. The plan permits changes to alternate concepts on a timely basis as the physics and engineering/technology studies evolve.

The total cost to develop fusion power from FY 1978 through the date of operation of the first demonstration reactor is found to be roughly $15 billion dollars in constant FY 1978 dollars. With such funding a demonstration reactor could operate in the time frame 1993 to 2005 depending on near-term funding profiles and progress. A reference case (called Logic III) which aims at a demonstration reactor in 1998 is treated in detail.

The Fusion Power Program Plan consists of five documents as follows:

ERDA-76/110/0	Executive Summary
ERDA-76/110/1	Volume I: Summary
ERDA-76/110/2	Volume II: Long Range Planning Projections
ERDA-76/110/3	Volume III: Five Year Plan
ERDA-76/110/4	Volume IV: Five Year Budget and Milestone Summaries

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Stephen O. Dean

Stephen O. Dean, Chairman
Fusion Power Planning and
Priorities Committee

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I. INTRODUCTION

Within the Energy Research and Development Administration, the Division of Magnetic Fusion Energy is responsible for the development of fusion power using magnetic confinement. Previous Fusion Power Research and Development Plans (e.g., WASH 1290, February 1974) have focused on the near term (next five years) program required to provide the necessary base technology and physics for fusion power development and to provide the physics demonstrations which would justify embarking on Experimental Fusion Power Reactors (EPR's) in the 1980's. These EPR's in turn would lead to a Fusion Power Demonstration Reactor before the year 2000. The nature and number of facilities required in the 1980's and 1990's and the associated R&D costs were not addressed in previous plans.

The Long Range Planning Projections presented in this volume, combined with the new 5-Year Program Plan (Volumes III and IV), constitute a new Fusion Power Program Plan. This Long Range Planning Projections volume treats the R&D program of the 1980's and 1990's and, in particular, considers some of the optional paths that may exist to a Demonstration Reactor for commercial application. The relationship among funding patterns, physics and engineering progress, and the date of achievement of the end goal is described.

The presently-established program goal of the fusion program is TO DEVELOP AND DEMONSTRATE PURE FUSION CENTRAL ELECTRIC POWER STATIONS FOR COMMERCIAL APPLICATION. More specifically, these projections assume that it is in the national interest to demonstrate, before the year 2000, safe, reliable, environmentally acceptable, economically competitive production of fusion power in a Demonstration Reactor that extrapolates readily to commercial reactors. Actual commercialization of fusion reactors is assumed to occur primarily through a developing fusion vendor industry working with Government and the electric utilities. A close coordination must evolve and be maintained among the potential vendors, electric utilities and the Government development effort. Hence it is also an objective of this plan to develop sufficient data that the utilities and industry can address all critical issues (e.g., capital and operating costs, reliability, safety,,etc.) involved in arriving at power plant purchase decisions. Short term objectives of the plan center around establishing the technical feasibility of the more promising concepts which could best lead to commercial power systems. Key to success in this effort is a cooperative effort in the R&D phase among Government, national laboratories, utilities and industry.

There exist potential applications of fusion systems other than central station electric plants. These include:

- Direct production of hydrogen gas and/or synthetic fuels
- Direct energy production for chemical processing
- Fissile fuel production
- Fission product waste disposal
- Fusion-fission hybrid reactors

These applications hold the possibility of increasing the overall impact of fusion power and of hastening its commercial application. The physical and economic characteristics of these potential applications have been analyzed only partially. Efforts are currently in progress to further evaluate the advantages and disadvantages of these applications; the present and planned programs will permit timely information on which decisions can be made to pursue these goals. The United States effort is a part of a much larger world effort. At present the U.S. effort is estimated to be about 1/3 of the world effort as measured by total man-years of effort. Extensive collaboration exists among all nations of the world active in fusion R&D. This is effected through bilateral arrangements, both formal and informal, for the exchange of information and manpower and through multilateral arrangements facilitated by the International Atomic Energy Agency and the International Energy Agency. A particularly close collaboration between the U.S. and the U.S.S.R. has developed during the past three years. This collaboration is supervised by a sixteen member group called the Joint (U.S.-U.S.S.R.) Fusion Power Coordinating Committee (JFPCC).

The program presented in these projections will permit the U.S. to achieve the desired end goal independent of any activity in another nation's program. However, coordination is maintained with other nations which insures that the steps taken in each country are complementary rather than duplicatory. This procedures leads to a reduction in the risk of failure in the overall effort. Examples of complementary large devices being built or considered in various nations at this time

are the Tokamak Fusion Test Reactor (TFTR) in the U.S., the Joint European Tokamak (JET) in Europe, the Japanese Tokamak-60 (JT-60) in Japan, and the Tokamak-20 (T-20) in the U.S.S.R. Differences among the devices can be noted, for example, in Figures V-3 and V-4 of Section V of this report.

The approach used in these projections is to consider the nature and schedule of the R&D program under five different funding assumptions called Program Logics. These are defined and discussed in Section II. Within each Logic there are a multiplicity of possible paths called Options which, in the near term, depend primarily on the outcome of the current generation of physics experiments. By way of example, Reference Options are selected and projected out to the operation of the DEMO. These are also discussed in Section II. The Logic III "Reference Option" is selected for detailed treatment in Section III. In this section, alternative options within Logic III are also discussed. Assumptions on costs and times to construct major facilities are presented in Section IV.

The treatments of Sections II, and III are primarily a "roll-forward" planning approach. The current program, the physics and engineering results required to justify a certain kind of next step, and the time required to build that next step is considered. It is also essential to good planning, however, to consider a "roll-back" planning approach. This is done in Section V by describing the nature and

timing of the desired R&D end product, namely, the Demonstration Power Reactor which would provide the base for commercialization. In the "roll-back" approach, the physics and engineering tests required for such a DEMO are identified and programs considered which would provide these tests. Clearly, these two approaches must both be used and be complementary for managing a successful fusion R&D program.

A tabular compilation of the estimated budgets required, by year, is presented in Section VI. All cost figures presented in this report are in constant FY 1978 dollars with the exception that the already-authorized projects, Tokamak Fusion Test Reactor (TFTR), Rotating Target Neutron Source (RTNS), and Intense Neutron Source (INS), are based on actual estimated costs to construct. Since the budget projections deal with matters 20-30 years in the future, the cost estimates are of necessity approximate. In Section VII, a bibliography of reference documents is given, including detailed planning reports and assessment documents for many of the program elements.

Data such as that presented in this plan can be used in the performance of cost/benefit analyses which will provide quantitative supporting information to help decide whether increased funding at some level is desirable. The basic framework for performing such cost/benefit analyses is being constructed by ERDA contractors.

II. PROGRAM LOGICS

A. General Considerations

The most significant policy and technical variables that affect the pace of the fusion program are

Policy Variables:

- The perceived NEED for fusion power.
- The nation's INTENT (what is expected by when? What priority does the program have?)
- FUNDING

Technical Variables:

- PHYSICS RESULTS
- ENGINEERING RESULTS

Because NEED, INTENT, and FUNDING are finally decided by others, the fusion program requires a number of plans by which the program can be conducted. The following plans, referred to as LOGICS, are considered.

LOGIC I. LEVEL OF EFFORT RESEARCH

Research and development are supported at an arbitrary level in order to develop basic understanding. (If this pace were continued, a practical fusion power system might never be built.)

LOGIC II: MODERATELY EXPANDING, SEQUENTIAL

Funds are expanding but technical progress is limited by the availability of funds. Established commitments are given funding priority but new projects are not started

until funds are available. In spite of limited funding a number of problems are addressed concurrently. (At this rate, a fusion demonstration reactor might operate in the early 21st century.)

LOGIC III: AGGRESSIVE

The levels of effort in physics and engineering are expanded according to programmatic need, assuming that adequate progress is evident. New projects are undertaken when they are scientifically justified. Many problems are addressed concurrently. Funding is ample but reasonably limited. (This program would be aimed at an operating demonstration reactor in the late 1990's.)

LOGIC IV: ACCELERATED

A great many problems are addressed in parallel and new projects are started when their need is defined. Fabrication and construction are carried out on a normal basis with enough priority to minimize delays. The availability of funds is still limited but a secondary factor in program planning and implementation. (This approach would be aimed at demonstration reactor operation in the early to mid-1990's.)

LOGIC V: MAXIMUM EFFECTIVE EFFORT

Manpower, facilities and funds are made available on a priority basis; all reasonable requests are honored immediately. Fabrication and construction are expedited on a priority basis so that completion times for major facilities are reduced to a practical minimum. (An operating demonstration plant around 1990 would be the program goal.)

Although the five Logics are most easily distinguished by costs and end-goal dates, it should also be noted that the degree of risk varies among Logics. Risk can increase under faster-paced Logics. On

the other hand, risk can decrease with higher budgets due to increased effort and partial overlapping of facility goals. It is not possible to quantify the net change in risk among the Logics in general; it is necessary, however, to assess the risk at every point along the way.

The interplay among policy variables, technical variables and program logics is shown in Figure II-1. Real world requirements as perceived by the Division of Magnetic Fusion Energy (DMFE) determine the program goals and objectives and, as perceived by ERDA, OMB, and Congress, fix the policy variables. An interaction takes place between the Division and ERDA, OMB and Congress, and eventually ERDA, OMB and the Congress determine which LOGIC the program is to follow. The goals and objectives, as modified by the policy variables prescribe the R&D program scope. The choice of LOGIC influences the activity within the program scope and a specific path (called a Logic Option) emerges. The results from following that option constitute the technical variables which the Division evaluates in the process of proposing the program goals and adjusting objectives.

B. General Assumptions

The tokamak is currently the most promising approach to fusion, and is closer to achieving a demonstration reactor for commercial application than other fusion concepts. The major effort, world-wide is devoted to tokamaks, but active programs in alternate concepts (e.g., mirrors and high-beta systems) exist in the U.S. and elsewhere. The mirror and toroidal theta pinch are the major Alternate Concepts in the U.S. The plan permits changes to alternate concepts on a timely basis as the physics and engineering/technology studies evolve.

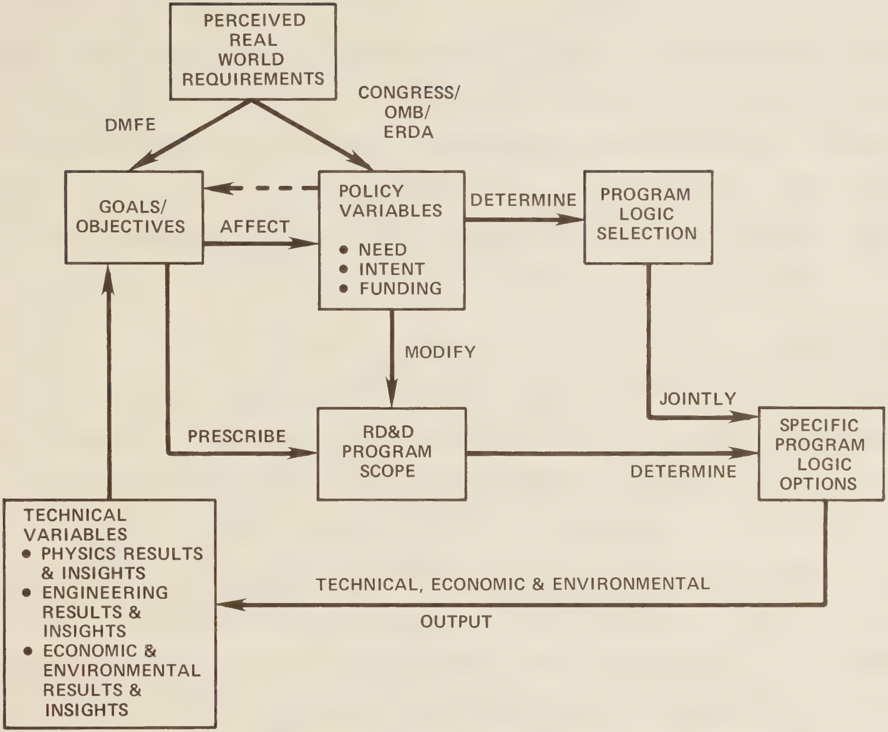


Figure II-1

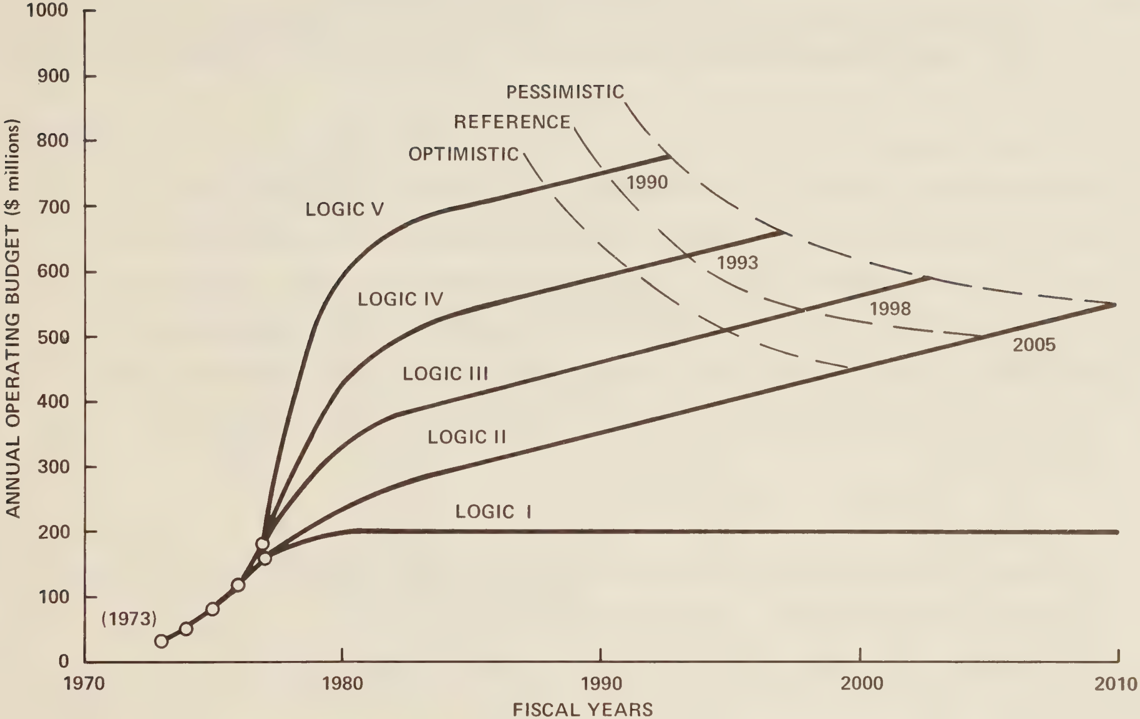
DMFE PLANNING METHODOLOGY

Other alternate concepts, each with a particularly promising feature as a fusion reactor, are also being supported in the world-wide fusion community. Leading among these are the Elmo Bumpy Torus (EBT), linear theta pinch, toroidal Z-pinch, imploding liners, and Tormac. The physics of these other alternate concepts is less well understood, their achievements are more modest, and relatively little effort has gone into reactor designs. Nonetheless, they are supported for the promise they hold for eventual reactor systems. Most concepts can also be considered as candidates for fusion-fission hybrid reactors and for engineering or materials test reactors (FERF/ETR).

C. The Five Program Logics

The Program Logics, numbered I through V are differentiated grossly according to approximate funding levels (Figure II-2). The funding is such that the funding level for Program Logic I will result in a DEMO far out in time, while the funding level for Program Logic V will result in a DEMO as soon as is practically possible. It should be noted that the degree of "pessimism" or "optimism" that one assumes substantially effects the projected date for operation of the DEMO. The projected operating date for a DEMO will also be affected by the degree of "risk" the program is willing to accept in moving from one step to the next. Clearly it is possible to aim at the same dates with lower funding, or earlier dates with the same funding if higher risks are taken, i.e., if less R&D and fewer demonstrated results are required to justify succeeding steps.

Figure II-2



FUSION R&D PROGRAM OPERATING BUDGET AND LOCI OF DEMO OPERATING DATES FOR LOGIC I THRU V

Each Program Logic can be described in terms of four key parameters; namely, the number of facilities, the physics and engineering parameters to be obtained from each facility, the times for initiation and completion of each facility, and the degree of overlap between completion and initiation of adjacent facilities.

1. Program Logic I

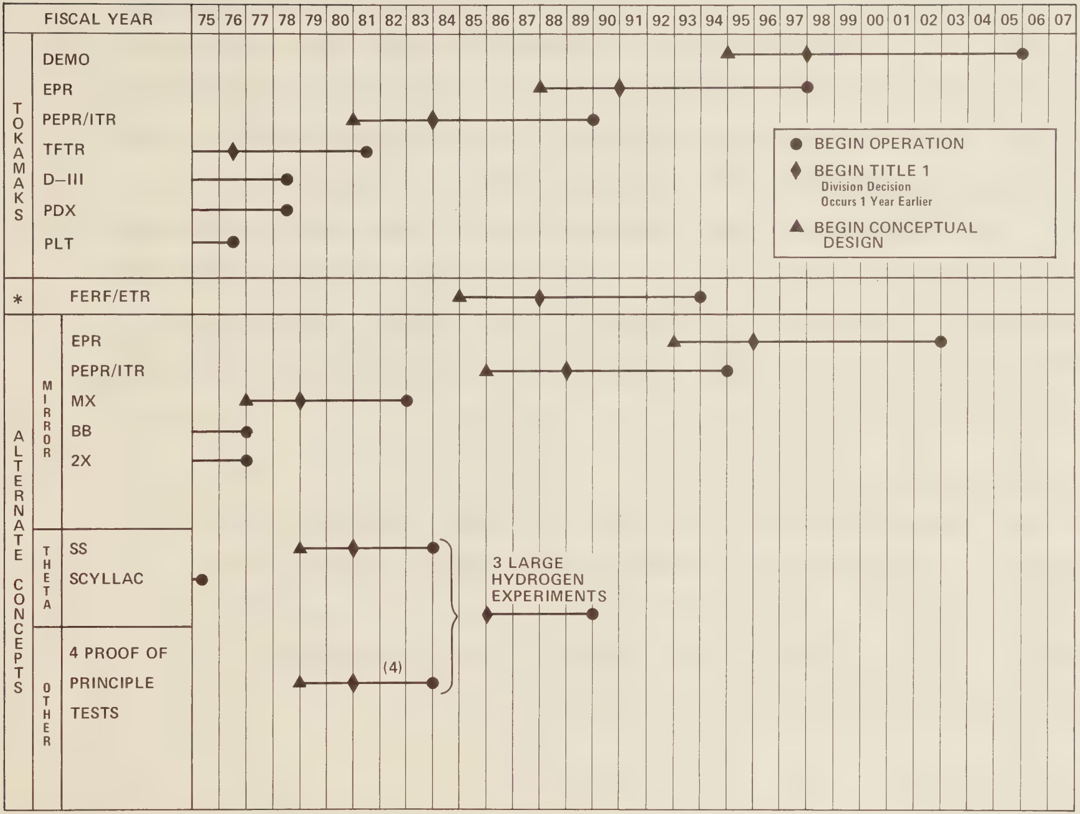
The funding level for Logic I is sufficiently low that the fusion program is carried out as a level of effort research program, and a DEMO is achieved far into the future if at all. There are insufficient funds to construct major facilities, except possibly large hydrogen experiments. Logic I would maintain the capability to develop fusion power but a decision to shift to a higher Logic would be required before a firm schedule could be postulated. The cost to develop a demonstration reactor under Logic I is therefore indeterminate.

2. Program Logic II

The Logic II Reference Option is shown in Figure II-3. Under the Logic II Reference Option, a DEMO would operate in 2005. Major devices are sequential, but no overlap exists between the operation of one device and the initiation of Title I funding of the succeeding device.

Figure II-3

LOGIC II REFERENCE OPTION



*MAJOR ENGINEERING FACILITY (SEE FIGURE III-7)

Minimal facilities are constructed, and moderate construction times for each facility are assumed. Minimal supporting facilities (not shown) for technology development exist. The devices listed in Figure II-3 are the following: Demonstration Reactor (DEMO), Experimental Power Reactor (EPR), Prototype Experimental Power Reactor or Ignition Test Reactor (PEPR/ITR), Tokamak Fusion Test Reactor (TFTR), Doublet III (D-III), Poloidal Divertor Experiment (PDX), Princeton Large Torus (PLT), Fusion Engineering Research Facility or Engineering Test Reactor (FERF/ETR), Large Mirror Experiment (MX), Baseball Mirror Device (BB), 2X Mirror Device (2X), Staged Scyllac (SS). The characteristics of the major new facilities (DEMO, EPR, PEPR/ITR, and TFTR) are given in Section IV. For planning and costing purposes, it is assumed that a selection process takes place among the various concepts so that a DEMO for one concept and EPR's for two concepts result.

a. Tokamak Assumptions

Four major devices are postulated after Doublet III; namely TFTR, PEPR/ITR, EPR, and DEMO. In addition, a major engineering facility (FERF/ETR), which may be a tokamak is constructed. There is a three year gap between the operation of TFTR and the beginning of PEPR/ITR, due to delays in results from supporting facilities, but PEPR/ITR, EPR, and DEMO are sequential.

b. Alternate Concepts Assumptions

- Mirror Assumptions

Three major devices past 2X/BB are postulated; namely MX, PEPR/ITR and EPR. Gaps exist between the operation of major facilities and initiation of the next step in order to fully evaluate results of each device before designing succeeding devices. Much technology development is derived from Tokamak facilities. This Logic could result in a Mirror DEMO (not shown) by 2011 (see Figure II-8).

- Theta-Pinch and Other Alternate Concept Assumptions

Three concepts, including Staged Scyllac, are examined in parallel on a moderate scale for proof-of-principle tests. Once proof-of-principle has been established, the most promising concept is evaluated further in a large hydrogen experiment which operates in 1989. This Logic could result in a Theta Pinch or Other Alternate Concept DEMO (not shown) by 2014 (see Figure II-8).

3. Program Logic III

The Logic III Reference Option is shown in Figure II-4. Under the Logic III Reference Option a DEMO would operate in 1998. More engineering support facilities are constructed and they are initiated earlier in time than under Logic II (details of cost and schedule are presented in Sections III and VI).

a. Tokamak Assumptions

Four major devices are postulated beyond Doublet III; namely TFTR, PEPR/ITR, EPR and DEMO. In addition a major engineering facility (FERF/ETR), which may be a tokamak, is constructed at an earlier date (by five years) than in Logic II.

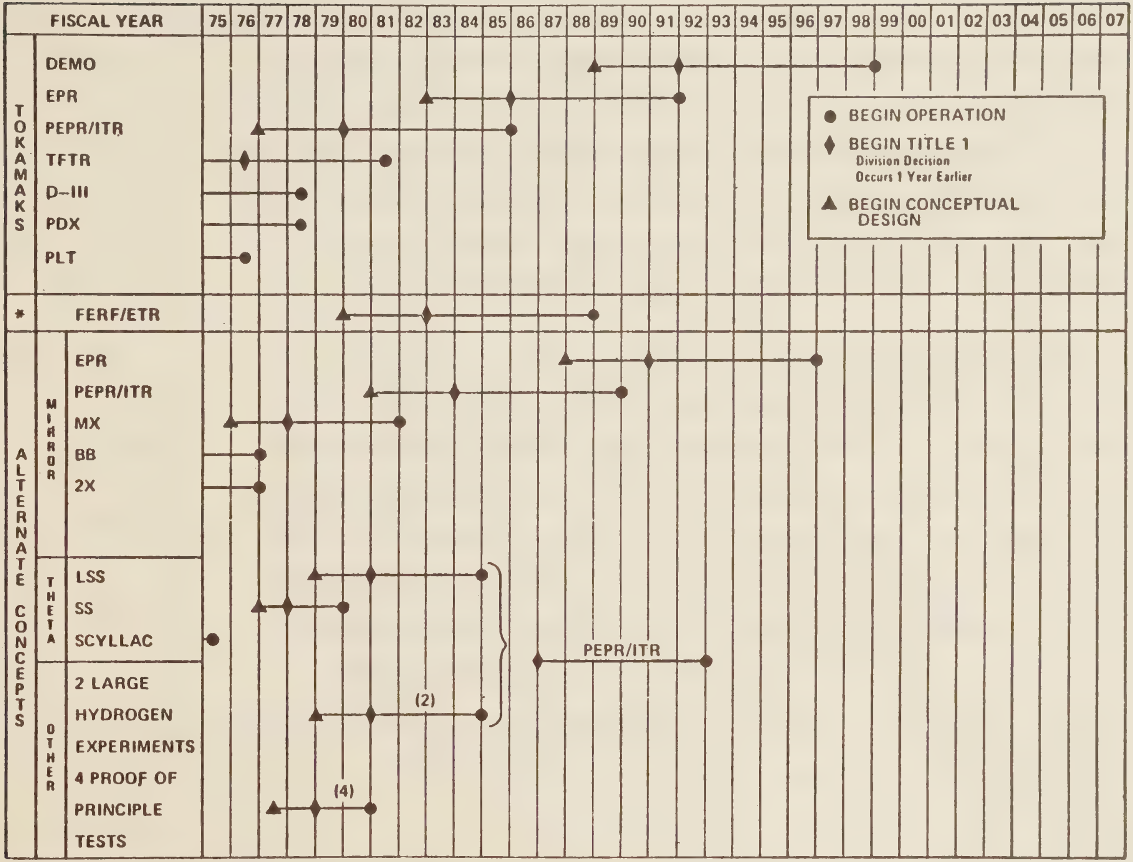
b. Alternate Concepts Assumptions

- Mirror Assumptions

Three major devices past 2X/BB are postulated; namely MX, PEPR/ITR and EPR. Compared to Logic II, a smaller gap (by four years) is assumed between the operation of MX and the initiation of PEPR/ITR. The FERF/ETR could be a mirror. This Logic could result in a mirror DEMO (not shown in Figure II-4 but see Figures II-5 and II-8) by 2004.

Figure II-4

LOGIC III REFERENCE OPTION



*MAJOR ENGINEERING FACILITY

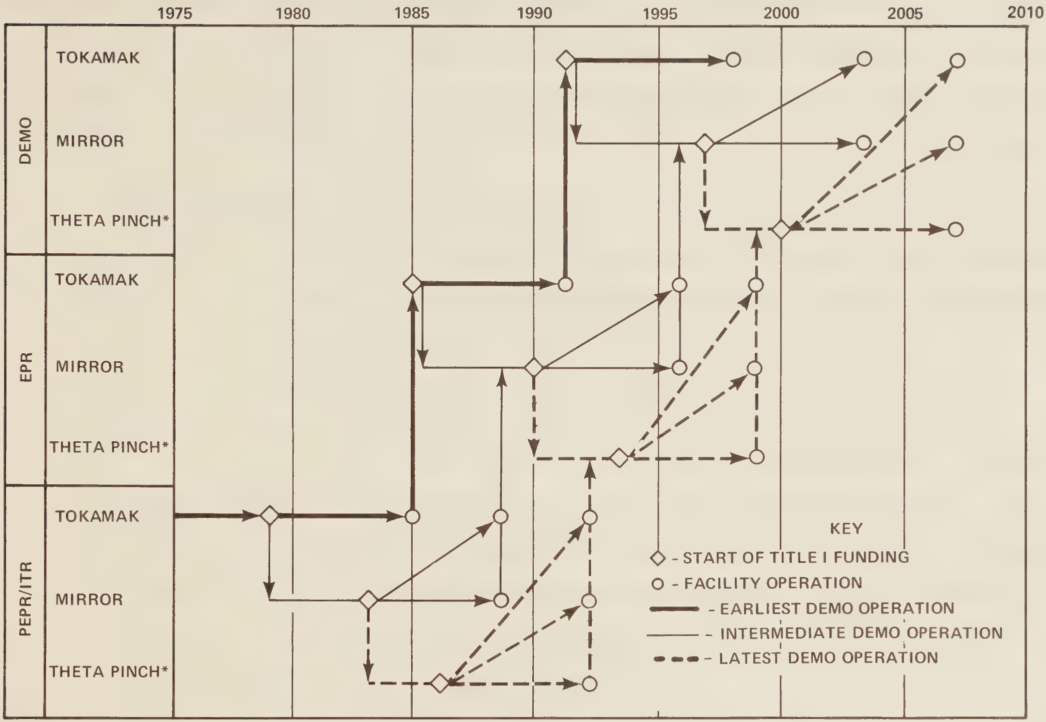
- <u>Theta Pinch and Other Alternate Concept Assumptions</u>

Five concepts, including Staged Scyllac, are examined in parallel on a moderate scale for proof-of-principle tests. Once a proof-of-principle has been established the most promising concepts are evaluated in large hydrogen experiments (LHX). Three LHX's, including Large Staged Scyllac, are assumed. After operation of the LHX's, one concept is selected for a PEPR/ITR. This Logic could result in a Theta Pinch or Other Alternate Concept DEMO (not shown in Figure II-4, but see Figures II-5 and II-8) by 2007.

- <u>Logic III Alternate Paths</u>

As decision dates occur for major facilities, it is possible that the decision will be to wait for further information. This is shown in Figure II-5, in which the program path alternatives for the Logic III Reference Option are presented. The circles represent facility operation dates and the diamonds indicate the initiation of Title I funding based upon a decision made the previous year. Note, for example, the first decision along the PEPR/ITR tokamak line. The result of this decision will be to either construct a tokamak PEPR/ITR or delay until more information becomes available for both tokamaks and mirrors. Assuming that the result of the decision is to wait,

LOGIC III REFERENCE OPTION PROGRAM PATH ALTERNATIVES



* OTHER ALTERNATE CONCEPTS WOULD FOLLOW THE THETA PINCH PATH

the next identified decision point is along the mirror PEPR/ITR line. This decision can result in three alternatives: (1) construct a tokamak PEPR/ITR; (2) construct a mirror PEPR/ITR; (3) delay until more information becomes available for all three approaches to magnetic fusion.

A decision made for one confinement concept (say tokamak PEPR/ITR) will not prevent a second decision, at a later point in time, for a second confinement method (say mirror or advanced concept PEPR/ITR).

The figure shows that the earliest possible Fusion Power Demonstration Reactor would be a tokamak operating around 1998. Note that this operation date could be delayed until 2004 (and could be a mirror) if the 1979 decision resulted in a decision to delay selection of the PEPR/ITR until 1983. This delay would be reduced if one were willing to permit a "continuum" of decision points between 1979 and 1983.

4. Logic IV

The Reference Option for Logic IV is shown in Figure II-6. Overlaps exist among most major devices; additional support facilities (not shown) to those in Logic III are constructed. Risk in completing the DEMO by a specified date is increased due to the device overlaps, but risk is decreased by the data obtained from the additional R&D effort and facilities.

a. Tokamak Assumptions

As in Logic III, four major devices past Doublet III are postulated; TFTR, PEPR/ITR, EPR, and DEMO. A major engineering facility (FERF/ETR), which may be a tokamak, is constructed. Some degree of overlap exists among all these devices, and their construction times have been shortened by one year from those assumed in Logic III. This Logic results in a Tokamak DEMO by 1993.

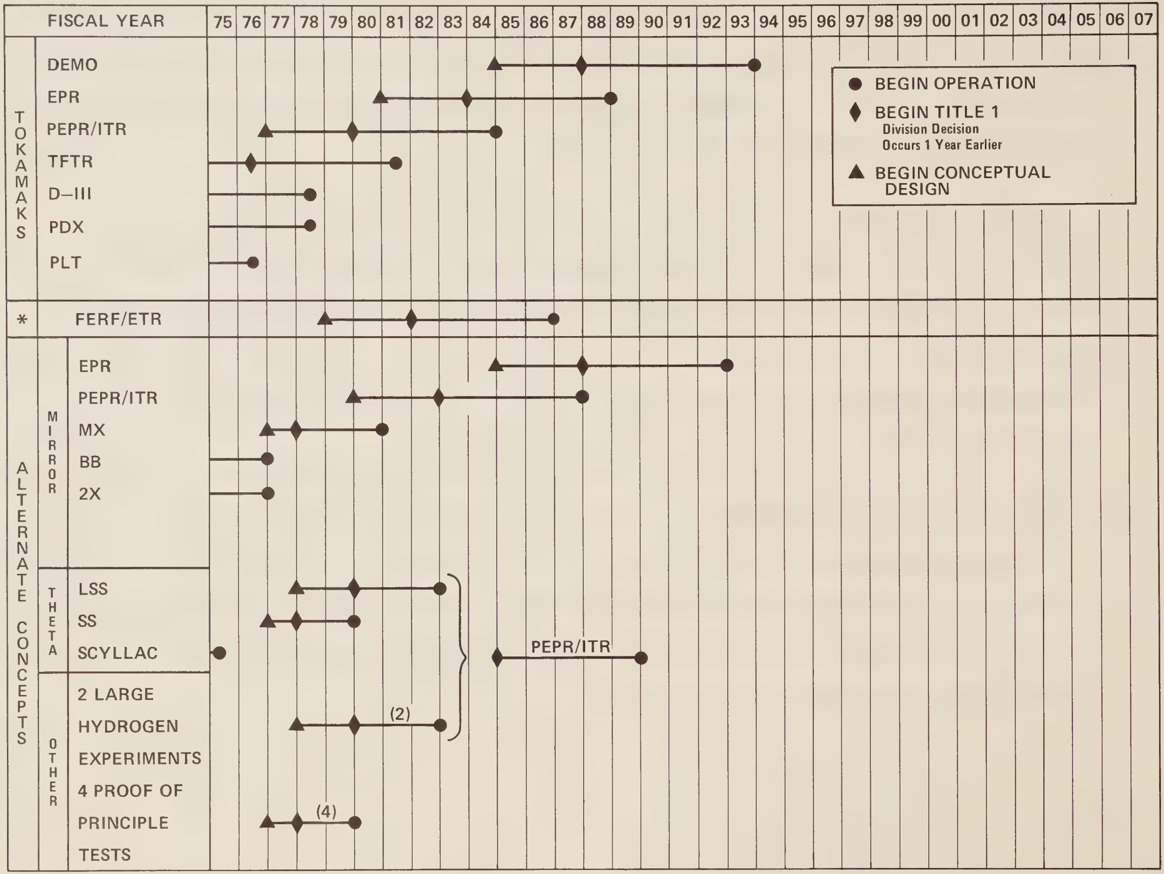
b. Alternate Concepts Assumptions

- Mirror Assumptions

Three major devices past 2X/BB are postulated; MX, PEPR/ITR, and EPR. The EPR is initiated the year of operation of PEPR/ITR. This Logic results in a Mirror DEMO (not shown) by 1998 (see Figure II-8).

Figure II-6

LOGIC IV REFERENCE OPTION



*MAJOR ENGINEERING FACILITY (SEE FIGURE III-7)

- <u>Theta Pinch and Other Alternate Concept Assumptions</u>

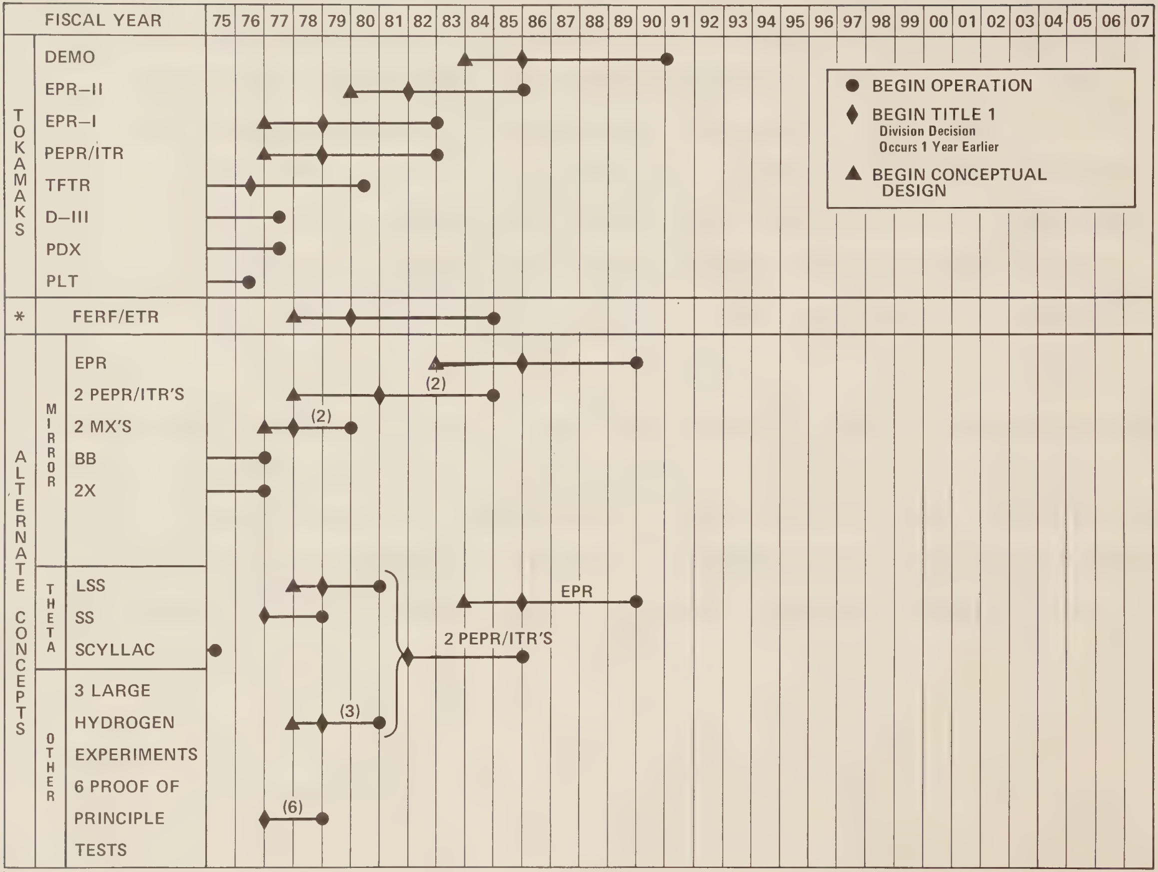
Five advanced concepts, including Staged Scyllac, are examined in parallel for proof-of-principle experiments on a somewhat shortened time scale as compared to Logic III time scales. After proof-of-principle experiments have been completed, three large hydrogen devices, including Large Staged Scyllac, are constructed in parallel, although the construction times are shortened by one year compared with those of Logic III. One PEPR is initiated, two years after operation of the large hydrogen devices and is constructed on a one year shorter time scale than those in Logic III. This Logic could result in a theta pinch or other alternate concept DEMO (not shown) by 2000 (see Figure II-8).

5. Logic V

The Reference Option for Logic V is shown in Figure II-7. Overlaps exist among all major devices; all device construction times have been shortened, and many parallel major and supporting facilities are constructed. Risk of completing a DEMO by a specified date is increased substantially due to increased overlaps among adjacent devices. As in Logic IV, risk will be decreased substantially by the addition of parallel devices and supporting facilities. Evaluation of the net changes in risk

Figure II-7

LOGIC V REFERENCE OPTION



*MAJOR ENGINEERING FACILITY (SEE FIGURE III-7)

due to these competing effects and the cross impacts of these effects would require substantial additional study compared to that which has occurred to date in preparing these planning projections.

a. Tokamak Assumptions

Five major facilities past Doublet III are postulated; namely, TFTR, PEPR/ITR, EPR-I, EPR-II, and DEMO. A major engineering facility (FERF/ETR) which may be a tokamak, is constructed. This logic leads to a DEMO by late 1990.

b. Alternate Concepts Assumptions

- Mirror Assumptions

Five major facilities past 2X/BB are postulated; namely 2 MX-sized devices, 2 PEPR/ITR's, and 1 EPR. This Logic could lead to a Mirror DEMO (not shown) by 1994 (see Figure II-8).

- Theta Pinch and Other Alternate Concept Assumptions

Seven advanced concepts, including Staged Scyllac, are examined in parallel on the shortest feasible timescale. Four large hydrogen experiments, including Large Staged Scyllac, are designed to operate two years after proof-of-principle experiments. Two DT burning facilities (PEPR/ITR's) would operate following completion of the large hydrogen experiments. One EPR would be designed based on

results from the large hydrogen experiments, but before results are obtained from PEPR's. A DEMO (not shown) could be constructed to operate by 1994 (see Figure II-8).

D. Cost and Schedule Summary

A summary of the operating dates projected for the first DEMO, by Logic and by concept, is presented in Figure II-8. Also presented in Figure II-8 is the total cost to develop the first DEMO from FY 1978 through date of initial operation of the first DEMO. These costs are in constant FY 1978 dollars. Note that these estimates indicate that the total cost of ~ $15B to develop the first DEMO is approximately independent of LOGIC.

The operating budget profiles for Logics I through V were presented in Figure II-2. The costs presented in Figure II-2 must be supplemented by the costs for equipment and for major facilities (PACE). These are computed in detail in Section VI. A profile of the yearly total costs for the Logic III Reference Option is shown in Figure II-9.

Figure II-8

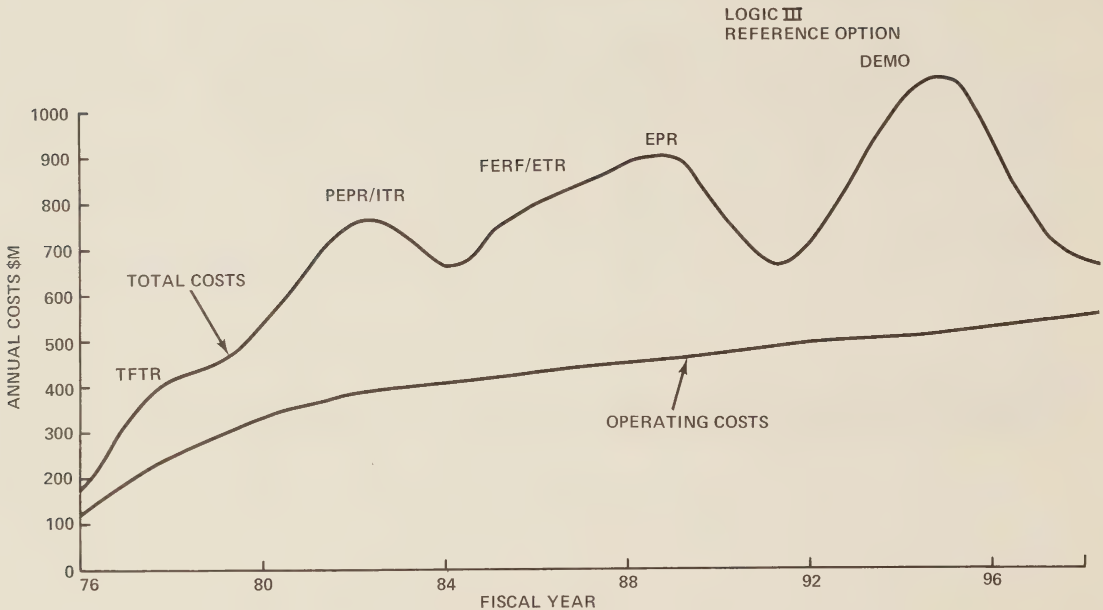
Projected Operating Dates for the Demonstration Power Reactor and Total Estimated Costs* for the Five Logics

	Tokamak	Magnetic Mirror	Theta Pinch and Other Alternate Concepts	Total Cost $B
Logic I	indeterminate	indeterminate	indeterminate	indeterminate
Logic II	2005	2011	2014	16.3 over 28 years
Logic III	1998	2004	2007	15.5 over 21 years
Logic IV	1993	1998	2000	14.8 over 15 years
Logic V	1990	1994	1994	20.1 over 13 years

* Total cost (in constant FY 1978 dollars) of program from FY 1978 to the date of operation of first DEMO.

Figure II-9

TOTAL PROGRAM ANNUAL COSTS vs. TIME
FOR THE LOGIC III REFERENCE OPTION



III. AN AGGRESSIVE (LOGIC III) PROGRAM

Logic III is chosen for a more detailed discussion. The definition of this Logic is:

> LOGIC III: AGGRESSIVE
>
> The levels of effort in physics and engineering are expanded according to programmatic need, assuming that adequate progress is evident. New projects are undertaken when they are scientifically justified. Many problems are addressed concurrently. Funding is ample but reasonably limited. (This program would be aimed at an operating demonstration reactor in the late 1990's.)

A. Assumptions

The following general assumptions were used in developing Logic III:

- Tokamaks are presently the most promising approach to achieving commercial fusion power.

- The next step in the tokamak program will be based upon the physics and engineering/technology results available in 1979.

- Of the Alternate Concepts, mirrors currently are the most advanced; the next step in the mirror program (MX) will be taken in FY 1978 and the next step beyond that will be based upon the physics and engineering/technology results available in 1982.

- Theta Pinches and other alternate concepts are being explored to identify more promising reactor concepts with respect to physics, engineering and economics. The toroidal theta pinch is the most advanced of these; other alternate concepts are less developed but do demonstrate promise.

- A decision on the first major DT facility for the theta pinch or other alternate concept is based on the physics and engineering/technology results available in 1985.

- Supporting theory and experiment is available throughout the program and supporting facilities are built as required.

- Costs are calculated assuming that the tokamak program proceeds to the DEMO and that one Alternate Concept proceeds through an EPR. Prior to the Alternate Concepts EPR there would be a mirror PEPR and one PEPR which is either a theta pinch or one of the other alternate concepts.

B. Logic III Reference Option Overview

The general features of the Logic III Reference Option are shown in Figure III-1. The present experimental program consists of several small and medium-sized hydrogen experiments (most notably the ORMAK and Alcator Tokamaks, the 2XIIB Mirror, and the Scyllac Theta Pinch) and the larger PLT at Princeton which came

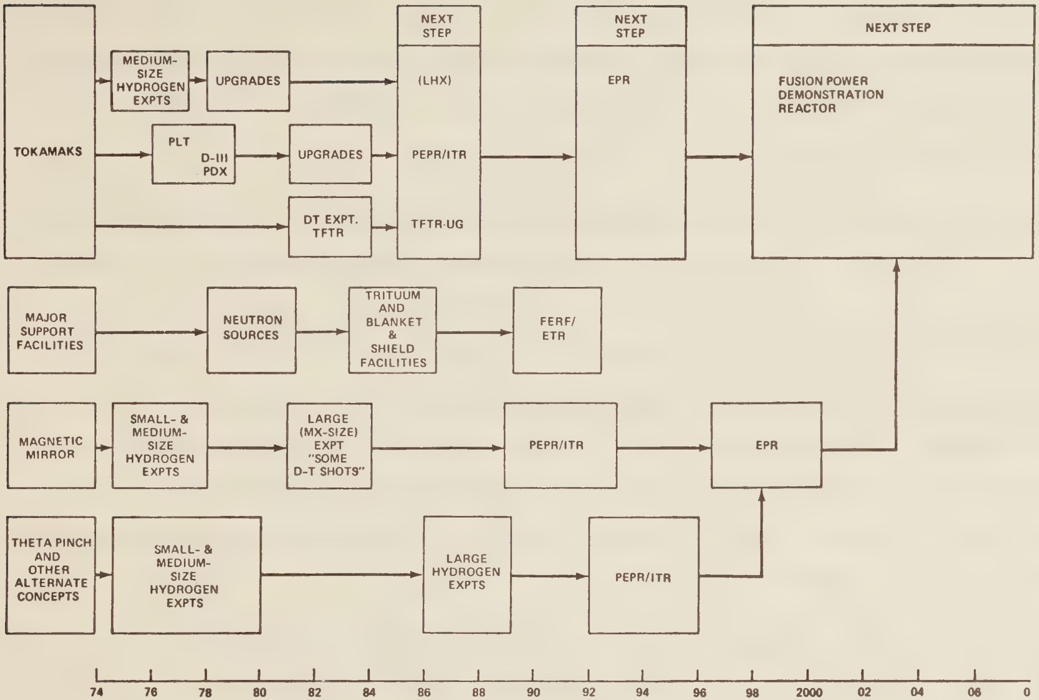


Figure III-1 General Features of the Logic III Reference Option

into operation in December 1975. Two other large tokamaks, Doublet III at General Atomic and PDX at Princeton, are in fabrication and scheduled to operate in early 1978. The first DT burning tokamak, the Tokamak Fusion Test Reactor (TFTR) is scheduled to operate in mid-1981. A large mirror experiment, called MX, has been proposed for operation in 1981.

Under a Logic III program each of these devices would be upgraded, primarily by adding more auxiliary heating power, to test physics scaling laws at higher temperature and higher power density (beta). In the mid- to late-1980's, large device(s) would be built assuming good results are obtained on earlier facilities. The next step in the tokamak line is assumed to be either a Prototype Experimental Power Reactor or an Ignition Test Reactor (PEPR/ITR). TFTR would be upgraded and possibly another large hydrogen experiment might be required. An engineering test reactor (FERF/ETR) is assumed, which could be a tokamak. By the early 1990's an Experimental Power Reactor (EPR) would be built, which makes net electrical power with high reliability. This device would be followed by the Fusion Power Demonstration Reactor in 1998.

The Magnetic Mirror Program is assumed to evolve from the present small- and medium-size experiments, most notably 2XII at Livermore, to a larger device in which a limited number of DT shots would be possible. A major objective of this device would be to test confinement scaling for longer times,

and to test methods for improving power balance, a prerequisite to the feasibility of a pure fusion mirror reactor. This would be followed by a PEPR device in the late 1980's. The FERF/ETR could be a mirror. This could be followed by an EPR operating in 1996 and a DEMO around 2004.

For the other Alternate Concepts, larger hydrogen experiments, such as the Large Staged Scyllac, are assumed to operate in the mid-1980's, followed by a PEPR/ITR in the early 1990's. Next could come an EPR in the late 1990's and a DEMO around 2007.

For costing purposes of Logic III, 3 PEPR/ITR devices; 1 FERF/ETR, 2 EPR's, and 1 DEMO are assumed.

Depending on progress and periodic assessments not all the devices and facilities projected in this plan would necessarily be built.

C. Critical Parameter Assessments

Decisions to move ahead, mark time, retreat, change approach, etc., are based on assessments of the status of the physics and engineering/technology at a given point in time. These assessments include a prognosis on the implications of our current understanding for future commercial fusion reactors. These assessments are called "critical parameter assessments" and currently are scheduled to take place in 1979 for tokamaks, in 1982 for magnetic mirrors and in 1985 for the toroidal theta pinch and other alternate concepts.

Although these assessments clearly involve complex scientific/technical issues, the projected results of these assessments are described herein in simpler terms. Each of the critical parameters is assessed by assigning a "good", "fair", or "poor" rating to that part of the assessment and an overall rating of "good", "fair", or "poor" is then assigned to the physics and engineering/technology parts of the assessment separately. These latter ratings are used in deciding the nature of the best next step in the program.

For tokamaks the definitions of the critical parameters and the proposed definitions of the "good", "fair", or "poor" ratings are as follows:

Tokamaks

Physics

(a) Beta - an assessment of the magnitude of the plasma beta that can be assumed for a Demo.

Good - > 8%
Fair - 6-8%
Poor - < 6%

(b) Scaling - an assessment of the implications for a reactor of confinement time scaling with parameters such as temperature, density, current, etc.

Good - Better than "trapped ion" shown in Figure 17 of WASH-1295.
Fair - Approximately equal to "trapped ion" scaling
Poor - Worse than "trapped ion" scaling

(c) Impurities - an assessment of how complex the impurity control techniques required in a reactor will be

Good - No impurity control required in demo
Fair - Simple impurity control techniques adequate for demo
Poor - Complex impurity control techniques required

Engineering/Technology

(d) Magnets - an assessment of the strength of toroidal magnetic field that can be assumed for demo

Good - Field at coil $\gg$8T
Fair - Field at coil ~ 8T
Poor - Delayed development

(e) Pulsed Coil and Power Supply - an assessment of the technology of matched superconducting pulsed coil, power supply, and energy storage systems.

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(f) Heating - an assessment of the technology of heating subsystems that can be assumed for the next step.

Good - High power, high efficiency
Fair - High power, low efficiency
Poor - Delayed development

(g) Fueling - an assessment of the technology of plasma refueling.

Good - Demonstrated
Fair - Development progressing well
Poor - Delayed development

(h) Materials - an assessment of the knowledge of materials properties - particularly surface properties - of reactor materials.

Good - Demonstrated reactor-grade materials
Fair - Development progressing well
Poor - Delayed development

Engineering/Technology (continued)

(i) Blanket/Shield and First Wall - an assessment of the technology of blanket, shield, and first wall.

Good - Development progressing well
Fair - Delayed development
Poor - Major difficulties foreseen

(j) Tritium Fuel Cycle - an assessment of the technologies of tritium fuel cycle technology.

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(k) Radiation Engineering - an assessment of the technology of remote maintenance, assembly, disassembly, and other engineering aspects associated with the radiation environment.

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(l) Vacuum Technology - an assessment of toroidal and beam vacuum technology

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(m) Commercialization - an assessment of the attractiveness of the concept for eventual use in a commercial environment.

Good - More attractive than competitive system
Fair - Competitive with other energy systems
Poor - Economic competitiveness doubtful

For Mirrors the critical parameters are:

Mirrors

Physics

(a) Q - an assessment of the net energy gain from the plasma that can be assumed for a demo.

Good - $Q > 2\text{-}3$
Fair - $Q = 0.5$ to 2-3
Poor - $Q \leqslant 0.1\text{-}0.5$

Engineering/Technology

(b) Magnets - an assessment of the strength of toroidal magnetic fields that can be assumed for demo.

Good - Field at coil $\gtrsim$ 12T
Fair - Field at coil > 8T
Poor - < 8T

(c) Efficiency of Power Recirculating System - an assessment of the efficiencies of the power handling subsystems projected for a DEMO.

Good - Multiplying blankets, high wall temperature, multi-stage direct converter
Fair - Standard blanket, steam cycle, single stage direct converter
Poor - Direct converter development delayed

(d) Heating - an assessment of the technology of heating subsystems that can be assumed for the next step.

Good - High power, high efficiency
Fair - High power, low efficiency
Poor - Delayed development

(e) Materials - an assessment of the knowledge of materials properties of reactor materials.

Good - Demonstrated reactor-grade materials
Fair - Development progressing well
Poor - Delayed development

(f) Blanket/Shield and First Wall - an assessment of the technology of blanket, shield, and first wall.

Good - Attractive designs developed for demo
Fair - Development progressing well
Poor - Delayed development

(g) Tritium Fuel Cycle - an assessment of the technologies of tritium fuel cycle technology

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(h) Radiation Engineering - an assessment of the technology of remote maintenance, assembly, disassembly, and other engineering aspects associated with the radiation environment.

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(i) Vacuum Technology - an assessment of vacuum technology.

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(j) Commercialization - an assessment of the attractiveness of the concept for eventual use in a commercial environment.

Good - More attractive than competitive system
Fair - Competitive with other energy systems
Poor - Economic competitiveness doubtful

For the toroidal theta pinch the critical parameters are:

Toroidal Theta Pinch

Physics

(a) MHD Confinement - an assessment of the confinement time, τ, that can be assumed for a demo relative to MHD time scales, τ_{MHD}.

(b) Confinement Transport - an assessment of plasma confinement, τ, relative to classical transport, τ_c.

Engineering/Technology

(c) Initial Heating - an assessment of methods for preparing ~ 1 keV plasma for adiabatic compression to ignition, including the technologies (high voltage, first wall insulators) for producing these plasmas.

(d) Pulsed Energy Storage - the assessment of pulsed magnetic or inertial energy systems for adiabatic compression in large theta pinches and the implementation of such technology for use in commercial reactor systems.

(e) Materials - an assessment of the knowledge of materials properties - particularly surface properties - of reactor materials.

Good - Demonstrated reactor-grade materials
Fair - Development progressing well
Poor - Delayed development

(f) Blanket/Shield and First Wall - an assessment of the technology of blanket, shield, and first wall.

Good - Attractive designs developed for demo
Fair - Development progressing well
Poor - Delayed development

(g) Tritium Fuel Cycle - an assessment of the technologies of tritium fuel cycle technology.

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(h) Radiation Engineering - an assessment of the technology of remote maintenance, assembly, disassembly, and other engineering aspects associated with the radiation environment.

Good - Technology demonstrated
Fair - Development progressing well
Poor - Delayed development

(i) Commercialization - an assessment of the attractiveness of the concept for eventual use in a commercial environment.

Good - More attractive than competitive system
Fair - Competitive with other energy systems
Poor - Economic competitiveness doubtful

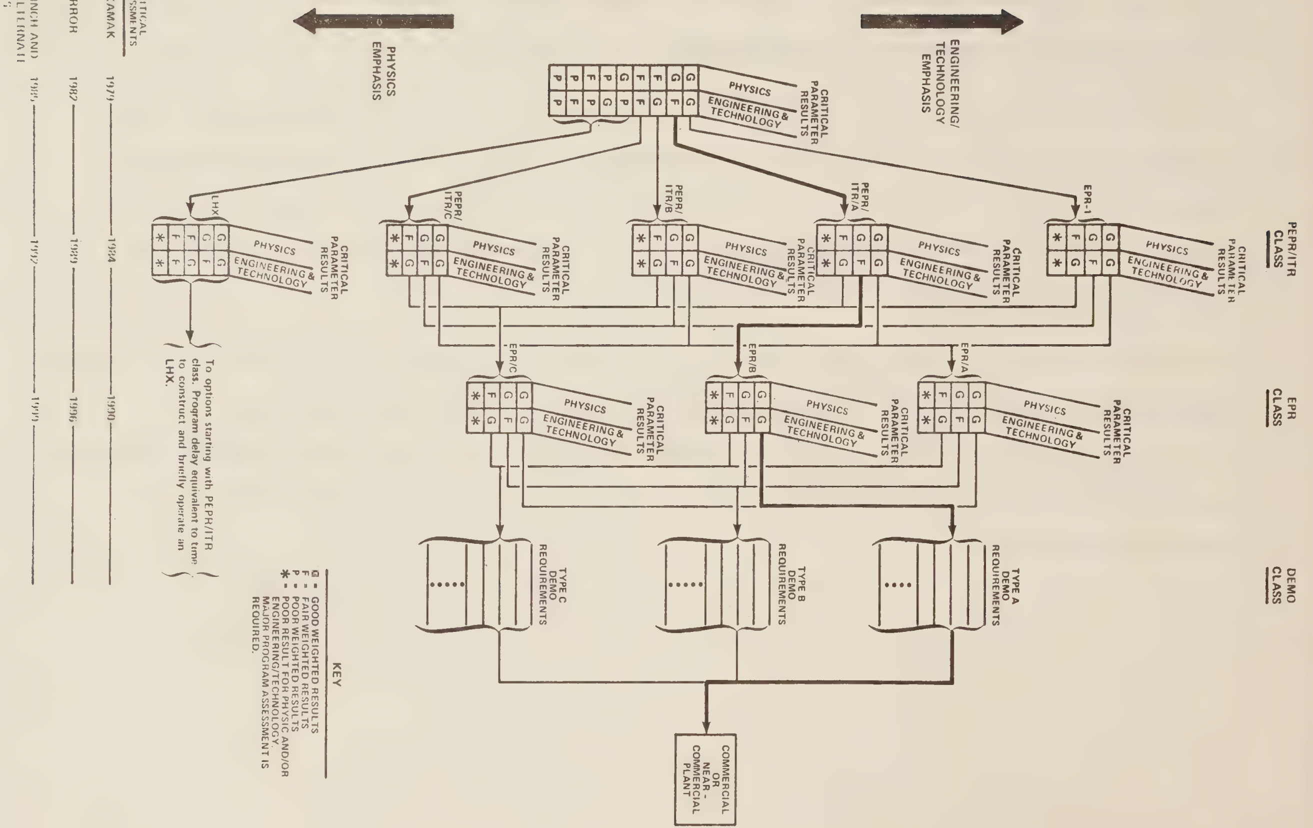
Figure III-2 is a schematic of the critical assessments process. It presents possible sequences of increasingly ambitious facilities, starting with current generation hydrogen experiments and culminating in the operation of a commercial or near commercial fusion power plant early in the next century.

The particular choice of the type of facility to be constructed at any step is determined basically by the level of success for both physics and engineering/technology criteria of the preceeding experiment(s). Further, there is a distinction determined by the level of success of physics criteria as compared with that for engineering/technology criteria. In general, the objectives of successive facilities are driven by the less successful results of their precursers.

For example, consider a typical path (heavy line) in Figure III-2. In 1979, tokamak physics and engineering/technology results will be on hand and assume that these are "good" and "fair", respectively. The next step, a PEPR/ITR/A, would have more engineering than physics objectives since, presumably, the 1979 physics were well in hand but more effort was indicated for engineering/technology (since this was evaluated only as fair).

Figure III-2

Critical Assessments Schematic



It should be noted that there are "Critical Parameter Results" indicated by asterisks. This means that either or both the physics and engineering/technology criteria evaluation had a poor result. This event would suggest a major program assessment, the results of which cannot be determined a priori. It also should be noted that similar results in the large hydrogen experiments (critical assessments for tokamaks, mirrors, and advanced concepts in 1979, 1982, and 1985 respectively) could lead to one subsequent large hydrogen experiment and, perhaps, a sequence of PEPR, EPR, and DEMO facilities.

The dates for critical assessments for each fusion approach is presented along the bottom of Figure III-2. These critical assessment dates key into the Logic III Reference Option program path alternatives.

D. Reference Options

In the planning process, assumptions must be made on the range of possible physics and engineering/technology results and the time at which these results will be forthcoming. This gives rise to a multiplicity of potential paths for each approach to fusion power, called "Options". Analysis shows that many of these results lead to decisions to build large devices which are similar in general

character, although they may differ in timing and in physics and engineering detail. Consequently the different options are characterized primarily by the nature of the next major facility to which the particular option path leads. Description of different options is given by specifying selected variables.

1. For Tokamaks, the following variables specify the options:

   (1) The physics prototype for the next step.

   (2) Assessment of critical parameter results achieved by 1979.

   (3) The general nature of the device to be built as the next step.

   (4) The initiation and completion target dates for the next step.

   (5) The general nature of the device to be built as the following step.

   (6) The initiation and completion dates for that step.

   (7) The general nature of the device to be built as the following step.

   (8) The initiation and completion dates for that step.

A matrix of possible tokamak options is shown in Figure III-3. In Column (3), "Critical Parameter Results by CY 1979", the assessment is shown by giving a good to poor rating for the physics and engineering/technology assessment as discussed in Section III-C.

Figure III-3

Logic Option Matrix for Tokamaks

Option	Description	Results of Critical Parameter Assessment in 1979: Physics	Eng. Techn.	Best Next Step	Completion Date	Best Next Step	I/C	Best Next Step	I/C
1. Reference	D-Shaped	G	F	PEPR/ITR FERF/ETR	79/85 82/88	EPR	85/91	DEMO	91/98
2. Optimistic	Doublet	G	G	EPR-I	79/85	EPR-II	84/90	DEMO	88/95
3. Pessimistic	Circular	F	F	LHX PEPR/ITR	79/84 85/91	EPR	91/97	DEMO	98/05
4. Reassessment	Any	P		Reassess in 1982 based upon further results from upgrades and TFTR					
5.	High Field	G	G	PEPR/ITR	79/85	EPR	85/91	DEMO	91/91
6.	High Field	G	F	Reassess					
7.	Doublet	G	F	PEPR/ITR	79/85	EPR	85/91	DEMO	91/98

The first option shown is the "Reference Option". The characteristics of this option are:

- The physics assessment is "good", e.g., tokamak reactors are expected to operate with betas greater than 8%; confinement scaling is better than the "trapped ion" scaling shown in Figure 17 of WASH 1295; simple impurity control techniques are sufficient.

- The engineering/technology assessment is "fair", e.g., large NbTi superconducting magnets can be built for devices in the mid-80's; high power, but low efficiency neutral beams have been developed.

- A PEPR/ITR is judged to be the best next step. It has an ignited DT plasma and is probably superconducting, but it does not have a full power conversion system to make electricity.

- The PEPR/ITR is initiated as an FY 1980 line item at a total PACE cost of $400M. It requires six years to build and operates in October 1985.

- An engineering test reactor, FERF/ETR is initiated as an FY 1983 line item at a total PACE cost of $500M. It requires six years to build and operates in October 1988.

- The next step after PEPR/ITR is an "EPR". This Experimental Power Reactor makes electricity, has good plant availability and more advanced materials technology than the class of EPR's labeled "EPR-I" in Option 2.

- The EPR is initiated as a FY 1986 line item at a total cost of $800M. It requires six years to build and operates in October 1991.

- The next step after EPR is the Fusion Power Demonstration Reactor. It is initiated as a FY 1992 line item at a total cost of $1,200M. It requires seven years to build and operates in October 1998.

The optimistic option for the tokamak assumes that both physics and engineering assessments are "good" and that the hoped-for advantages of the doublet configuration have been demonstrated. In this case, the next steps would be an EPR-I, followed by EPR-II, followed by a DEMO operating in 1995.

The pessimistic option assumes "fair" ratings for both physics and engineering/technology in 1979. In this case the PEPR/ITR would be initiated in series with a new large hydrogen experiment. The DEMO would be delayed until 2005.

If either physics or engineering/technology is rated "poor" in 1979, a reassessment would be made, probably leading to a shift in program emphasis to the mirror or other alternate concept.

Other options obviously exist. A few of these are shown as options 5, 6, and 7 in Figure III-3.

2. For Magnetic Mirrors, which is the most advanced of the alternate concepts, the following variables specify an option:

(1) The physics prototype of the next step.

(2) Assessment of critical parameter results achieved by CY 1982.

(3) The nature and initiation/completion dates of succeeding steps.

A matrix of possible mirror options is shown in Figure III-4. The critical parameters which are evaluated as well as the definitions of specific ratings are discussed in Section III-C.

The characteristics of the Mirror Reference Option are:

- The physics of mirrors, as assessed in 1982, leads to the conclusion that there are good prospects for achieving $Q \geq 2$-3 in a reactor (defined as the ratio of fusion power to injected beam power).

- The technology of large NbTi magnets and of high power low efficiency beams has been demonstrated.

- The next step after MX is a Prototype Experimental Power Reactor. PEPR is initiated as a FY 1984 line item at a total cost of $400M and operates in 1989.

- The next step after PEPR is a power-producing EPR. It has all the basic features of a complete commercial reactor system including high-efficiency power handling components and more advanced materials technology. The EPR is initiated in FY 1990 and is completed in 1996 at a cost of $800M.

- The next step after EPR is a Fusion Power Demonstration Reactor. It is initiated as a FY 1997 line item at a total cost of $1,200M. It requires seven years to build and operates in 2004. The actual decision to proceed would depend on critical assessments of the tokamak program in CY 1990 and the mirror program in CY 1996.

The optimistic option for the mirror contains the same steps as the Reference Option except that even better prospects in physics and engineering/technology decrease risks and permit earlier starting dates for program steps. Good physics prospects might result in a simplification of the mirror reactor design.

Figure III-4

Logic III: Option Matrix for Mirror and Toroidal Theta Pinch Alternate Concepts

Option	Physics Prototype	I/C	Results of Critical Parameter Assessment-1982 Physics	Eng/Tech.	Best Next Step	Initiation/ Completion Date	Best Next Step	I/C	Best Next Step	I/C
Mirror										
1. Reference	MX		G	F	PEPR	83/89	EPR	90/96	DEMO	97/04
2. Optimistic	MX		G	G	PEPR	82/88	EPR	88/94	DEMO	93/01
3. Pessimistic	MX	77/81	F	F	LHX PEPR	82/87 88/94	EPR	95/01	DEMO	02/09
4. Reassess			P	P	-					
5. Fusion/Fission	MX	77/81	F	F	F/F PEPR	83/89	F/F DEMO	90/96		
6. FERF/ETR	MX	77/81	F	F	FERF/ETR	82/88				
Toroidal θ-Pinch			Assessment-1985							
1. Reference	Large		G	F	PEPR/ITR	86/92	EPR	93/99	DEMO	00/07
2. Optimistic	Staged	80/84	G	G	PEPR/ITR	86/89	EPR	90/96	DEMO	97/04
3. Pessimistic	Scyllac		F	F	LHX PEPR/ITR	85/90 91/97	EPR	98/04	DEMO	05/12
4. Reassess			P	P	-					

Nb_3Sn magnets and efficient beams are assured. The DEMO is finished three years sooner. In the pessimistic mirror option it is assumed that physics prospects in 1982 are limited to conventional mirror systems with Q of 0.5 - 2 to 3. It is still uncertain whether power handling efficiencies can be pushed to high values; high-field magnets and high efficiency beams have not yet been developed. With the goal of a pure fusion reactor, the next step would be to establish a new experimental direction incorporating the mirror principle and aimed at increasing Q. PEPR would be initiated in series with a new large hydrogen experiment. "Poor" ratings in either physics or engineering/technology in 1982 would result in a reassessment, possibly leading to a shift to toroidal theta pinch or other alternate concept. The DEMO would be delayed until 2009.

Another mirror option (Option 5, Figure III-4) is for fusion-fission. In this option it is assumed that it has been decided by 1982 that a goal of the program is the breeding of fuel for fission reactors or the building of hybrid reactors for power. In this case, the next step beyond MX is the FF-PEPR; a device nearly identical to PEPR except that the plasma is surrounded by a fission type blanket and it can produce net power.

The fusion-fission reactor requires only modest technology such as NbTi magnets, positive ion beams, modest wall temperatures, and simple direct conversion (if any). It also only requires that Q be greater than about 0.5. The next step beyond the FF-EPR can be a Demonstration Reactor operating in 1996.

Another option (Option 6) is FERF/ETR. In this option it is assumed that mirrors have been selected to be the Materials and Engineering Test Reactor for the entire fusion program. A FERF/ETR operating in 1988 would be the goal.

3. For the Toroidal Theta Pinch a matrix of possible options is also shown in Figure III-4. The critical parameters which will be evaluated in 1985 are discussed in Section III-C. The characteristics of the Reference Option are:

- A reactor can be assumed to have a good gross confinement times compared to MHD times and good particle confinement times compared to classical transport times.

- Development is progressing well on the critical engineering/technology problems.

- The next step after LSS is a Prototype Experimental Power Reactor/Ignition Test Reactor. PEPR/ITR is initiated as an FY 1987 line item at a total cost of $400M and operates in 1992.

- The next step after PEPR/ITR is an Experimental Power Reactor. EPR is initiated as an FY 1994 line item and operates in 1999.

- The next step after EPR is the Demonstration Reactor. DEMO is initiated as an FY 2000 line item and operates in 2007.

The optimistic option for the toroidal theta pinch assumes that the PEPR/ITR can be built as a modification of the Large Staged Scyllac, thus reducing the overall schedule by three years.

The pessimistic option assumes that "fair" ratings in 1985 require that PEPR/ITR be built in series with another large hydrogen experiment. This delays the DEMO until 2012.

A "poor" rating in either physics or engineering/technology would result in a reassessment which could lead to a decision to shift program emphasis to another alternate concept.

The Toroidal Theta Pinch concept could also lead to a fusion-fission option which is not shown in Figure III-4.

4. For the Other Alternate Concepts, a different approach to the development of the option matrix is chosen. Alternate concepts are pursued if they offer potential physics, engineering/technology or economic advantages. An aggressive but sequential alternate concepts program is maintained in Logic III to examine all of the potentially promising confinement approaches at least to the point of "proof-of-principle" tests (see Figure III-5). In particular about six proof-of-principle experiments would be completed by 1980-82. Large hydrogen experiments for the two most promising concepts

Figure III-5

Logic III: Option Matrix for Other Alternate Concepts

Option	Physics Prototype	I/C	Results of Critical Parameter Assessment-1985 Physics	Results of Critical Parameter Assessment-1985 Eng/Techn.	Best Next Step	I/C	Best Next Step	I/C	Best Next Step	I/C
Reference	LHX	81/85	G	F	PEPR/ITR	86/92	EPR	93/99	DEMO	00/07

Concept	Principal	I/C	LHX	PEPR/ITR	EPR	DEMO
EBT	EBT-II	78/80	Up to two large hydrogen experiments would be fabricated based on the most promising concepts. Initiation would occur in FY80-82 with completion in FY84-86.	One PEPR/ITR among theta pinch and other alts. would be fabricated based on '85 assessment of critical parameters	One EPR from all alternate concepts could be fabricated based on '89, '92 assessments of critical parameters.	One DEMO from among all fusion approaches could be fabricated based on '90, '96, '99 assessments of critical parameters.
TORMAC	TORMAC VI	78/80				
ZT	ZT-II	79/81				
Linear	Scylla IV-P Long Linear Expt.	74/76 78/82				
Liner	Linus I	78/80				

would then be initiated in the early 1980's and completed in FY 1984-86. One PEPR/ITR would be initiated in 1986 and completed in 1993. One EPR could be initiated in 1993 and completed in 1999. A DEMO could be initiated in 2000 and completed in 2007.

Due to the large number of alternate concepts being examined in the near term and the limited work done to date, it is not reasonable to develop quantitative definitions of critical physics and engineering parameters for alternate concepts other than the mirror and theta pinch discussed previously. However, there are critical assessment periods which occur naturally (1980-82 and 1984-86) at which time major comparative assessments would take place. The essential point of the planning assumptions for alternate concepts is that new concepts must be encouraged since there is a significant possibility that some concept will emerge that will extrapolate to an economically-competitive reactor system, albeit on a somewhat delayed schedule with respect to the mainline tokamak program as now envisaged.

New concepts can and will emerge. These will be incorporated into these planning projections as part of the continuing updating process. At the present time the principal alternate concepts which are being pursued are:

- Mirror
- Toroidal Theta Pinch (Scyllac) at the Los Alamos Scientific Laboratory

- Toroidal Z Pinch (ZT) at the Los Alamos Scientific Laboratory
- Elmo Bumpy Torus (EBT) at Oak Ridge National Laboratory
- TORMAC at Lawrence Berkeley Laboratory
- Linear Systems, including
    - Linear Theta Pinch
    - Long Solenoids with Various Heating Options Including Laser, E-Beam, etc.
- Imploding Liner

Figure III-6 represents the current estimates of specific facilities for these alternate concepts. Similar facilities would emerge for new concepts. Appraisal of all novel concepts is actively pursued in order to identify promising additions to these lists. Among those currently included are multiple mirrors, inertial electrostatic confinement, relativistic e-beam or ion-beam heated solenoids, surface magnetic confinement (SURMAC) and ion ring concepts.

5. Supporting Engineering Facilities are required. The principal ones envisioned are shown in Figure III-7 and described in Section IV. The engineering and materials test reactor (FERF/ETR) is the most costly of the supporting facilities.

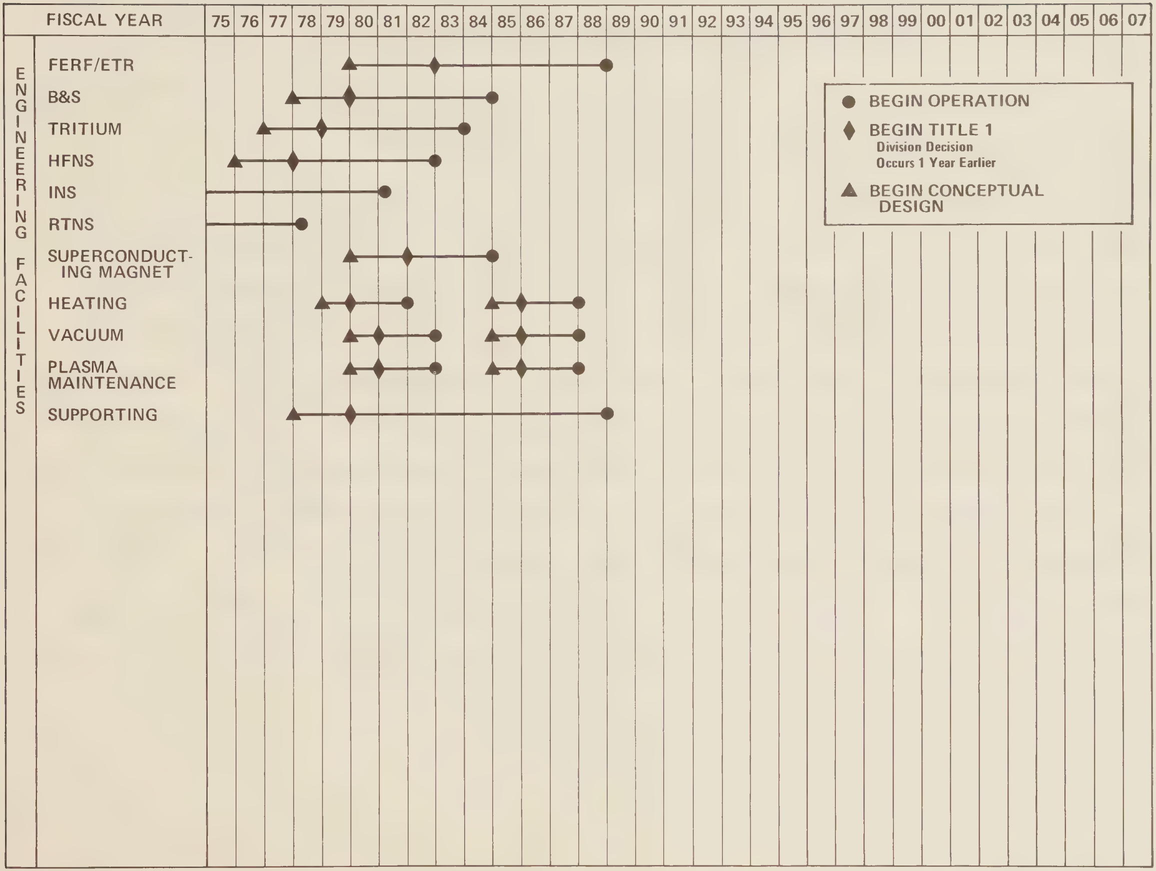
Figure III-6

Principal Other Alternate Concepts

Concept	Present Device	Next Step	Proof of Principle	Large Hydrogen Experiment
Bumpy Torus (ORNL)	EBT-I	EBT-S (77/77)	EBT-II (78/80)	(81/85)
Toroidal Bi-Cusp (LBL)	TORMAC V	TORMAC VB (76/77)	TORMAC VI (78/80)	TORMAC VII (81/84)
Toroidal Z-Pinch (LASL)	ZT-S	ZT-P (76/78)	ZT-II (79/81)	ZT-R (82/87)
Linear Theta-Pinch (LASL/MSNW)	SCYLLA IV-P PCX (CO_2/Solenoid)	- MOD PCX (78/79)	Long Linear (78/82) IHX (79/82)	Linear Feasibility (83/87) ITR (83/88)
Imploding Liners (NRL/LASL)	SUZY-II LN-1	LINUS-0 (76/77) LN-2 (77/78)	LINUS-1 (78/80) -	LINUS-2 (81/85) LNTR (82/87)

Figure III-7

ENGINEERING FACILITIES (LOGIC III)



6. FERF/ETR

Previous CTR planning documents have specified the need for a Fusion Engineering Research Facility to provide for tests of engineering components and subsystems and for extensive materials and component testing in a high flux fusion environment. Such information will be needed if fusion power technology is to become commercially viable at an early date. This section discusses options for obtaining this information and how the data obtained can feed into the overall program.

The key considerations on assessing the need for materials test facilities are the requirements on test volume, neutron flux, and the time required to obtain data at some specified goal fluence or damage level. Figure III-8 compares several of the presently contemplated materials irradiation facilities on the basis of flux, volume, time to reach a time integrated fluence of 10^{22} n/cm^2-sec (14 meV), construction cost and parameters that relate to operating cost. None of these facilities are in operation today. The Rotating Target Neutron Source (RTNS) and the Intense Neutron Source (INS) are approved and the High Flux Neutron Source (HFNS) is under consideration as an FY 78 line item. Currently data is being obtained from a relatively low performance RTNS, from existing low performance D-Be stripping sources, and from fission reactors.

Figure III-8

COMPARISON OF CURRENTLY DEFINED 14 MEV NEUTRON IRRADIATION FACILITIES

FACILITY	TEST VOLUME	MAX FLUX n/cm^2 - SEC (14 MeV)	ASSUMED AVAILABILITY	TIME TO REACH* FLUENCE OF 10^{22} n/cm^2 (14 MeV)	CONSTRUCTION COST	YEARLY POWER/ TRITIUM CONSUMPTION**
RTNS	Few CC's	$\sim 2 \times 10^{13}$	80%	~20 Years	5 M	< 5 Mw/200 g***
INS	Few CC's	$\sim 1 \times 10^{14}$	80%	~4 Years	26 M	< 5 Mw/4 g
HFNS	~10 CC's Few 100's of CC's ~1 - Liter	$\sim 10^{15}$ $>1 \times 10^{14}$ $>5 \times 10^{13}$	80%	~ ½ Year ~ 4 Years ~ 8 Years	~75 M	5-10 Mw/NA
Mirror FERF (UCRL 51617)	~100 Liters	$.5 \times 10^{14}$ (Low Field) 1.8×10^{14} (High Field)	70%	~9 Years ~2.5 Years	~.5 B	50–150 Mw/200 g 150–400 Mw/700 g
Tokamak ETR	~1,000 Liters	8×10^{13}	70%	~6 Years	.3-.5 B	300-400 Mw/5 Kg
EPR-1	~1,000 Liters	$2\text{-}6 \times 10^{13}$	40%	~13 to 40 Years	.5-1 B	?/4-8 Kg
Counter Streaming Ion Tokamak	< 1,000 Liters	$\sim 10^{13}$	70%	~45 Years	.2-.4 B	100 Mw/250 g
Alcator FERF	Surface of Torus ~5 M^2	$\sim 5 \times 10^{13}$	70%	~10 Years	50-100 M	200+Mw/250 g

* 4 Mw - Years/m^2 ** 1 Mw - Year Costs .05M to .5M Per Year Tritium Price is ~5-10$K/gm ***Most Can be Recovered

The fluence of 10^{22} is approximately equivalent to 4 MW years/m^2 integrated 14 meV dose and is considered to be the shortest lifetime which would be considered viable for a Demonstration Reactor. Four MW-yrs/m^2 is equal to two years of operation at 2 MW/m^2 or one year at 4 MW/m^2. DEMO reactor studies indicate that wall loadings in the range of 5 MW/m^2 may be needed for economic fusion power. Reasonable lifetimes would probably have to be greater than two years so one can see that ten MW years/m^2 might represent a more realistic end of lifetime exposure.

The highest fluxes shown in the table come from the HFNS which is a D-Li stripping source, and the high field mirror FERF. These facilities are far apart in required technology, test volume, and construction and operating costs. Although the HFNS is not a pure 14 meV source, the spectrum can be used to simulate the displacement damage and gas production expected in fusion reactor first walls.

None of the accelerator-based neutron sources have enough test volume to provide all the bulk irradiation data required for optimized commercial designs. In the case of nickel-containing alloys, fission reactors can be used to obtain most of the required data while the accelerator sources provide a basis for correlating this information to the fusion environment. For non-nickel-containing alloys, more accelerator sources or actual fusion reactor irradiations will be necessary.

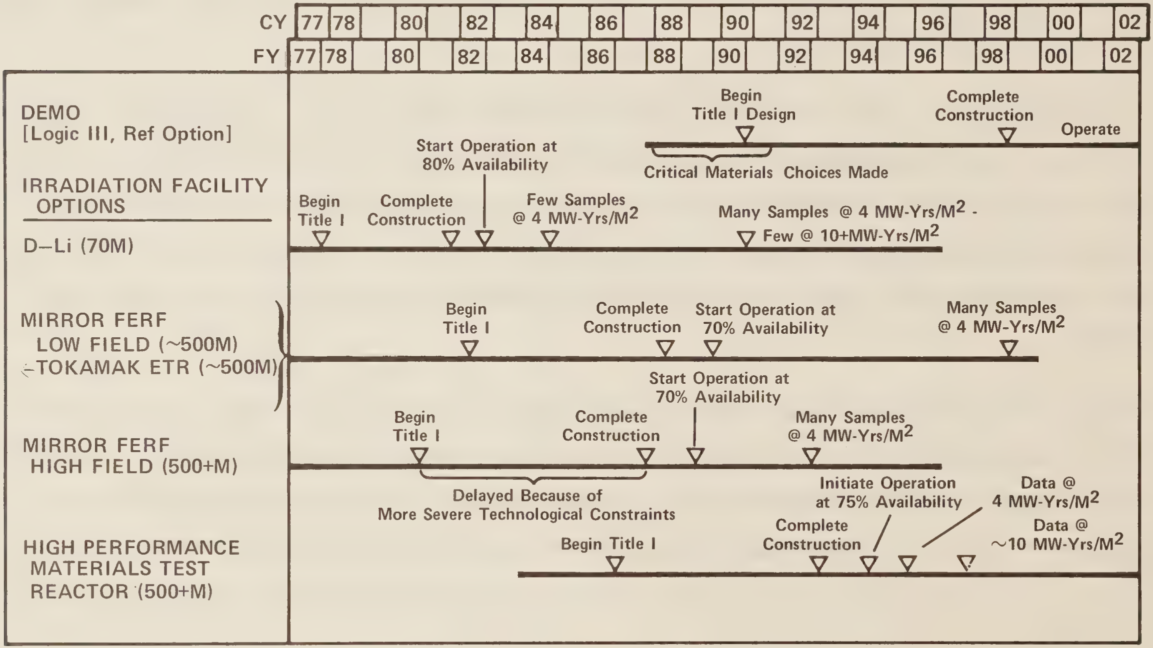
Figure III-9 shows when design data would be available from a range of high volume, high flux irradiation facilities. The Logic III Reference Option DEMO schedule is included to show how this data would feed into DEMO design. The mirror FERF and Tokamak ETR in the third and fourth lines are started at what is considered to be the earliest feasible date. The last line on the table is for a high performance materials test reactor which will be discussed later.

The Figure shows the earliest date when materials data at four MW-yrs/m^2 can be obtained for the HFNS and currently envisioned FERF/ETR. The only option for obtaining data to four MW-yrs/m^2 prior to the start of Title I design of the DEMO is the combination of HFNS and fission reactors. If the goal fluence on the DEMO material is greater than four MW-yrs/m^2 the mismatch between FERF/ETR input and DEMO design becomes more significant. The earlier DEMO dates in Logics IV and V also increase the mismatch.

Given that fusion environment data at goal fluence probably won't be available when the Logic III Reference Option DEMO materials choices are made, the objective of the FERF/ETR would be to obtain confirmatory data on the DEMO materials selection and to provide data for the first generation of commercial reactors. There are many situations where designs have been committed on the best data

Figure III-9

DESIGN DATA AVAILABILITY FROM POTENTIAL HIGH VOLUME, HIGH FLUX IRRADIATION FACILITIES



available at the time and confirmed by tests results that come in later. For the DEMO this might mean getting goal exposure data toward the end of DEMO construction and continuing to accumulate information which can set operational lifetime limits. Any data so obtained would automatically be available for early generation commercial reactors.

The last line of the figure shows a high performance materials reactor which serves this last function. It could be an advanced mirror or high beta tokamak which operates at a wall loading of about 5 MW/m^2. It is committed after the ultimate character of first generation commercial fusion reactors is defined and the ultimate limits of most confinement schemes are known. From the schedules for Logic III, Reference Option this is in about FY 1986. This reactor could be based on the best physics results available at the time and might therefore be a higher Q (lower power consumption) device than the currently contemplated FERF or ETR's. Accelerating the schedule by several years might also be possible if physics and technology results are optimistic.

As shown in the figure this reactor could provide very high fluence data (10 $MW\text{-}yrs/m^2$) by the time the DEMO begins operation. It would provide an extensive data base for commercial reactors, and would be committed only after the technical feasibility of fusion power is demonstrated.

Finally, because of previous operating experience on large fusion facilities, there would be a good chance of achieving the availability required for a materials test reactor.

The Logic III Reference Option contains a FERF/ETR in the time span beginning in FY 1983 and finishing at the end of FY 1988.

7. Fusion-Fission

A potentially attractive use of neutron-producing fusion processes is in fusion-fission configurations. Commonly called hybrids, fusion-fission energy systems appear to have three loosely coupled applications: fissile fuel breeding; electric power production, possibly with some fissile fuel breeding; and fission waste disposal (e.g., actinides), probably with electric power production. Among these, fuel production seems the easiest to achieve, but there are concommitant economic requirements which may not be possible to meet. Electric power production, with a byproduct of fissile fuel, appears to hold the greatest economic promise, but at the expense of machine subsystems which may be very difficult to design and maintain. Fission waste burning, in this time frame, will be the most difficult to achieve because of the required fusion neutron power density and the heat removal requirements.

Although the goal of the fusion program is the development of commercial fusion power, support is provided for study of fusion-fission energy systems. This is done because there is some evidence to suggest that there may be economic benefit derived from such systems, and that this benefit may become available at an earlier date than from pure fusion reactors. The possibility of earlier implementation principally arises from a relaxation of the physics requirements, and possibly, reactor subsystems requirements from the case of a pure fusion reactor.

The fusion-fission option has been examined for tokamaks, mirrors, and linear theta pinches as the neutron drivers.* Other new concepts may emerge which are attractive for this option. Recent work has focused on driven tokamaks (i.e., TFTR class) and mirrors as these approaches seem to promise the earliest demonstration and the highest likelihood of success. Because of preliminary results from econometric studies, the design objectives have been directed toward electric power generation, but recent work (mirrors) has investigated optimization for fissile fuel production. For both objectives considerable conceptual subsystem design has been performed in addition to neutronics and fuel cycle dynamics. However, these studies are very preliminary in nature and extensive work will be required to produce designs which are credible and can lead to Title I funding.

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*See "DCTR Fusion-Fission Energy Systems Review Meeting, December 4 and 5, 1974" ERDA-4.

There are four interrelated problem areas in fusion-fission concepts which must be solved self-consistently: fusion physics, reactor engineering, economics, and environment and safety. Selecting economics as the major class of governing variables, one must identify the likely product demands (and their values) when fusion-fission energy systems may be available. For example, one must select one or a combination of fissile fuel production, electric power production, and fission waste disposal and then try to assess the value of these products/services at the time that fusion-fission could be commercially implemented. This problem is further complicated by the possible mix of products/services that any given design may be capable of producing as well as the alternate fuel cycle and possible additional byproducts (e.g., synfuels, industrial process heat, and the like).

After the identification of the most likely economic scenario in which fusion-fission could be a part, then a selection can be made of the most suitable fusion and fission concepts which, when combined, would be expected to be commercially competitive and satisfy environmental and safety requirements. Detailed designs then can be developed over a period of a year or more and subsequently be subjected to critical anslyses of costs, credibility, and safety. At this point in time, preliminary conceptual designs are about half finished of two of the larger number of fusion-fission concepts which could be considered.

As an option for any of the magnetic confinement approaches, a fusion-fission system might come in one generation earlier than the pure fusion DEMO. For example, a fusion-fission DEMO corresponds roughly to a pure fusion EPR. The fundamental reason behind the possible earlier demonstration of the fusion-fission option is the relaxation of technical requirements discussed earlier.

The issue on whether to treat fusion-fission energy systems as a major objective of the fusion program has yet to be resolved. The fundamental question is whether it is needed at all and the answer only can be revealed by continuing assessment of fusion, fission, and alternative energy supply status and prospects.

8. Alternate Fuel Cycles

Several environmental drawbacks are commonly attributed to DT fusion power. First, it produces substantial amounts of neutrons that result in induced radioactivity within the reactor structure, and it requires the handling of the radioisotope tritium. Second, only about 20% of the fusion energy yield appears in the form of charged particles, which limits the extent to which direct energy conversion techniques might be applied. Finally, the use of DT fusion power depends on lithium resources, which are less abundant than deuterium resources.

These drawbacks of DT fusion power have led to the proposal of alternatives for longer term application -- for example, fusion power reactors based only on deuterium. Such systems are expected to (1) reduce the production of high energy neutrons and accordingly the need to handle tritium; (2) produce more fusion power in the form of charged particles; and (3) be independent of lithium resources for tritium breeding. It has also been suggested that materials with slightly higher atomic numbers (like lithium, beryllium, and boron) be used as fusion fuels to provide power that is essentially free of neutrons and tritium and that release all of their energy in the form of charged particles.

Although such alternatives to DT fusion power are attractive, there is an important scientific caveat. To derive useful amounts of power from nuclear fusion, it will be necessary to confine a suitably dense plasma at fusion temperatures (10^8 ^oK) for a specific length of time. This fundamental aspect of fusion power is expressible in terms of the product of the plasma density, n, and the energy confinement time, τ, required for fusion power breakeven (i.e., the condition of which the fusion power release equals the power input necessary to heat and confine the plasma). The required product, $n\tau$, depends on the fusion fuel and is primarily a function of the plasma temperature. Of all the fusion fuels under current consideration, the deuterium tritium fuel mixture requires the lowest value of $n\tau$ by

at least an order of magnitude and the lowest fusion temperatures by at least a factor of 5. When the plasma requirements for significant power generation are compared with the anticipated plasma performance of current approaches to fusion power, it is apparent that fusion power must initially be based on a deuterium-tritium fuel economy. However, the eventual use of alternate fuel cycles remains an important ultimate goal and consequently attention will be given to identifying concepts which may permit their ultimate use.

IV. ASSUMPTIONS ON DATES AND COSTS OF MAJOR FACILITIES CONSTRUCTION AND DESCRIPTION OF MAJOR FACILITIES

A. Assumptions on Dates and Costs of Major Facilities Construction

In order to provide a common set of ground rules for considering the different Logics and Options, a set of reference data was established for the costs of, and time required to fabricate, major facilities. These are to be used when developing new options unless the variants are clearly explained in each case.

Figures IV-1 to IV-3 show the Fiscal Years in which the "next step" major facilities would be initiated for the Reference Options in each Logic. In the upper left of each block is shown the month/year in which Title I money would begin and in the lower right the month/year in which operation would begin. Tokamak schedules are shown in Figure IV-1. Mirror schedules are shown in Figure IV-2. Theta Pinch and Other Alternate Concepts schedules are shown in Figure IV-3.

Figure IV-4 shows the time required to construct "next step" major facilities and Figure IV-5 shows the assumed cost ($M) of the "next step" major facilities for the various Logics. These costs represent

PACE costs only, in unescalated FY 1978 dollars. In Logic V the costs shown are 30% higher for the same facility. This is due to the assumed premium that would be required to obtain the necessary priorities to shorten the schedule.

Figure IV-6 shows the time required (years) to construct major support facilities in the various Logics. Figure IV-7 shows the assumed cost ($M) of these facilities. Again, these are unescalated FY 1978 PACE dollars.

Figure IV-8 gives the assumed funding profiles for major projects. Construction Times of two to eight years are included.

Figure IV-1

Fiscal Year of Initiation of "Next Step" Tokamak Major Facilities*

For the Reference Option in Each Logic

	I	II	III	IV	V
PEPR/ITR	-	10/83 FY 1984 10/89	10/79 FY 1980 10/85	10/79 FY 1980 10/84	10/78 FY 1979 10/82
EPR-I	-	-	-	-	10/78 FY 1979 10/82
EPR-II		10/90 FY 1991 10/97	10/85 FY 1986 10/91	10/83 FY 1984 10/88	10/81 FY 1982 10/85
DEMO	-	10/97 FY 1998 10/05	10/91 FY 1992 10/98	10/87 FY 1988 10/93	10/85 FY 1986 10/90

* Mo/Yr of initiation of Title I funding is shown in upper left corner of each block; Mo/Yr of initial operation is shown in lower right.

Figure IV-2

Fiscal Year of Initiation of "Next Step" Mirror Major Facilities*

For the Reference Option in Each Logic

	I	II	III	IV	V
PEPR/ITR	-	10/88 FY 1989 10/94	10/83 FY 1984 10/89	10/82 FY 1983 10/87	10/80 FY 1981 10/84
EPR	-	10/95 FY 1996 10/02	10/90 FY 1991 10/96	10/87 FY 1988 10/92	10/85 FY 1986 10/89
DEMO	-	10/03 FY 2004 10/11	10/97 FY 1998 10/04	10/92 FY 1993 10/98	10/89 FY 1990 10/94

* Mo/Yr of initiation of Title I funding is shown in upper left corner of each block; Mo/Yr of initial operation is shown in lower right.

Figure IV-3

Fiscal Year of Initiation of "Next Step" Alternate Concepts Major Facilities* Other Than Mirror

For the Reference Option in Each Logic

	I	II	III	IV	V
LHX	-	10/85 FY 1986 10/89	10/80 FY 1981 10/84	10/79 FY 1980 10/82	10/78 FY 1979 10/80
PEPR	-	10/91 FY 1992 10/97	10/86 FY 1987 10/92	10/84 FY 1985 10/89	10/82 FY 1983 10/86
EPR		10/98 FY 1999 10/05	10/93 FY 1994 10/99	10/89 FY 1990 10/94	10/85 FY 1986 10/89
DEMO	-	10/06 FY 2007 10/14	10/00 FY 2001 10/07	10/94 FY 1995 10/00	10/89 FY 1990 10/94

* Mo/Yr of initiation of Title I funding is shown in upper left corner of each block; Mo/Yr of initial operation is shown in lower right.

Figure IV-4

Time (Years) Required to Construct "Next Step" Major Facilities in the Various Logics

From Initiation of Title I to Operation

	I	II	III	IV	V
LHX*	4	5	5	4	3
PEPR/ITR	-	6	6	5	4
EPR-I	-	6	6	5	4
EPR-II	-	7	6	5	4
DEMO	-	8	7	6	5

* LHX time to construct for Tokamak program is as shown in table;
LHX time to construct for all Alternate Concepts is one year less than shown in table.

Figure IV-5

Cost ($M) to Construct "Next Step" Major Facilities in FY 1978 Dollars for

the Various Logics From Initiation of Title I to Operation

	I	II	III	IV	V
LHX*	100	200	200	200	260
PEPR/ITR	-	400	400	400	520
EPR-I	-	600	600	600	780
EPR-II	-	800	800	800	1040
DEMO	-	1200	1200	1200	1560

* LHX cost for Tokamak program is as shown in table.
LHX cost for all Alternate Concepts one-half cost shown in table.

Figure IV-6

Time (Years) to Construct Support Facilities in the Various Logics

From Initiation of Title I to Operation

	I	II	III	IV	V
Fusion Engineering Test Reactor/ Engineering Test Reactor (FERF/ETR)	-	6	6	5	4
Blanket & Shield Facility (B&S)	-	5	5	4	3
Tritium R&D Facility	-	5	5	4	3
High Flux Neutron Source (HFNS)	-	4	4	3	3
Intense Neutron Source (INS)	-	4	4	4	3
Rotating Target Neutron Source (INS)	-	2	2	2	2
Heating Technology Test Facility (HTTF)	-	2	2	2	1.5
Plasma Maintenance and Control Test Facilities (PM&CTF)	-	2	2	2	1.5
Vacuum Technology Facilities (VTF)	-	2	2	2	1.5
Superconducting Magnet Test Facility	-	*	*	*	*
Engineering Support Facility	-	-	*	*	*

* Time to construct these individual facilities ranges from 1 to 3 years

Figure IV-7

Cost ($M) of Support Facilities in the Various Logics

	I	II	III	IV	V
Fusion Engineering Test Reactor/ Engineering Test Reactor(FERF/ETR)	-	500	500	500	650
Blanket & Shield Facility (B&S)	-	50	50	50	65
Tritium R&D Facility	-	50	50	50	65
High Flux Neutron Source(s)(HFNS)	-	75	75	150	300
Intense Neutron Source (INS)	-	25	25	25	25
Rotating Target Neutron Source (RTNS)	-	5	5	5	5
Heating Technology Test Facility (HTTF)	-	30	30	30	40
Plasma Maintenance and Control Test Facilities (PM&CTF)	-	15	15	15	20
Vacuum Technology Facilities (VTF)	-	15	15	15	20
Superconducting Magnet Test Facility	-	30	30	30	40
Engineering Support Facilities	-	-	100	200	500

Figure IV-8

Assumed Facilities Funding Profiles

Initiate Title I Year	Percent of Pace Cost Per Year						
	2 Year Project	3 Year Project	4 Year Project	5 Year Project	6 Year Project	7 Year Project	8 Year Project
1	40	20	15	10	5	5	5
2	60	50	35	20	15	10	10
3		30	35	40	30	20	15
4			15	20	30	30	20
5				10	15	20	20
6					5	10	15
7						5	10
8							5

B. Description of Major Facilities

Many of the facilities which are discussed are not yet precisely defined. A list of these facilities as seen today is given in Figure IV-9 and discussed below. The descriptions are generally applicable to any confinement approach except as noted. An attempt has been made to group the types of reactor facilities in generic categories. It is recognized that when the time for decision nears, specific objectives of a proposed facility will depend on technical information and priorities at that time. Some specific facilities which have been proposed (e.g., Alcator FERF, Counter Streaming Ion Tokamak Engineering Facility, MRTX, etc.) do not really fall into the categories listed because of their unique characteristics relative to mainline facilities. These have been omitted to simplify this document and does not mean these proposals have been eliminated from consideration. They are treated in the detailed Five Year Plan (Volumes III and IV). A summary of the characteristics assumed for some of these facilities is shown in Figure IV-10.

Figure IV-9

Major Facilities

- Demonstration Fusion Power Reactor (DEMO)
- Experimental Power Reactor - II
- Experimental Power Reactor - I
- Prototype EPR/Ignition Test Reactor (PEPR/ITR)
- Fusion Engineering Research Facility/Engineering Test Reactor (FERF/ETR)
- Large Hydrogen Experiment (LHX)
- Tokamak Fusion Test Reactor (TFTR)
- Blanket and Shield Facility
- Tritium R&D Facility
- Superconducting Magnet Test Facility
- Rotating Target Neutron Source (RTNS)
- Intense Neutron Source (INS)
- High Flux Neutron Source (HFNS)
- Heating Technology Test Facilities
- Plasma Maintenance & Control Test Facilities
- Vacuum Technology Facility
- Supporting Facilities

Figure IV-10

SUMMARY OF MAJOR REACTOR FACILITIES

Device	Power Level	Plant Avail.	Plant Life	Pulse Length	Test Capability	Tritium Fuel Cycle	Fueling	Blanket	Remote Maintenance	Impurity Controls	Cost
TFTR	Reactor Power Densities	Low	5 Years	Short	D/T Burn Components	None	Test Fueling Concepts	Neutron Shield	Preliminary	Test Control Concepts	$230M
PEPR/ ITR	High–Q Reactor Level Plasma	Low	10 Years	Moderate	Probably S/C Magnets Blanket & Breeding Modules	Test Tritium Fuel Cycle	Demonstrate Moderate Fueling	Demonstrate Heat Removal	Moderate	Allow Moderate Burn	$400M
EPR	Steady State Reactor Power	Moderate (~50%)	15 Years	Long	Materials Application Modules	Reactor Tritium Fuel Cycle	Reactor Level Fueling	Complete High Temperature	Reactor Level Plant Maintenance	Allow Long Burn	$800M
Demo		High (~70%)	30 Years	Long	Materials Application Modules						$1200M
Comm'l Reactor		High (~70%)	>30 Years	Long	Applications Systems						$1000M

1. The Demonstration Fusion Power Reactor (DEMO) is the principal end objective in current fusion power program plans. It demonstrates safe, reliable electric power generation and has the following specific objectives:

- A few hundred MW_e net
- Plant availability 60-80% with high reliability
- Fuel breeding ~1.0
- Design and operating regime which extrapolates readily to commercial sized reactors
- Favorable economic scaling characteristics relative to alternate power systems
- Scaleable from EPR
- Impurity problems controlled
- Optimized thermal storage system to produce steady state power
- Uses materials with reasonable reserves
- Thirty Year Plant Life - Capable of being maintained
- First wall materials capable of lifetimes which are consistent with economic scaling
- Plant efficiency consistent with economic scaling
- Licensable
- This facility must lay the technical and economic groundwork to allow a decision on the rate of introduction of commercial plants. It is recognized that the initial commercial sized reactors may still be evolving toward optimized economical designs.
- Cost ~ $1.2B

2. The EPR-II is the prototype for the Demonstration Reactor. It will prove most of the physics and engineering required for the DEMO but at a smaller, less efficient scale. In the Reference Options of Logics II, III and IV where only one EPR is discussed, it is assumed to be EPR-II.

- Generation of net electrical power
- Thermal efficiency ($\gtrsim$ 20%)
- Attempts to attain 20-50% plant availability
- Demonstrates reactor plant maintenance systems
- Breeding modules with local BR > 1
- Complete High Temperature Blanket System
- Steady State Power Generation
- Duty cycle that scales to DEMO
- Demonstrate reactor tritium fuel cycle
- Capability to accommodate materials testing
- Prototype reactor safety pkg.
- Scaleable from the previous steps
- Scaleable to DEMO
- Cost $800M

3. The EPR-I is specified in some options as is the first DT test reactor step. Very good physics and engineering results are required to take this step. EPR-I will have the following objectives:

- Operate with high plasma Q
- Demonstrate the basic components and systems of a fusion power reactor
- Demonstrate scaling to a sustained reactor grade plasma
- Demonstrate capability to produce net electrical power
- Demonstrate reactor fueling
- Complete tritium fuel cycle and containment/cleanup systems
- Complete, high temperature blanket system
- Demonstrate breeding and use of alternate coolants in special blanket modules
- Cost \$600M

4. The Prototype Experimental Power Reactor or Ignition Test Reactor (PEPR/ITR) is defined as a major DT burning step for any of the fusion concepts. It may emphasize the physics of ignition or high plasma Q (ITR) or be a more engineering-oriented device prototypical of an EPR (PEPR). It is not required to produce electric power. Its characteristics are:

- DT burning - goal is to reach ignition or reactor level plasma Q; qualifies the physics of the EPR.
- Superconducting magnets (although the physics goal could be achieved in a non-superconducting device).
- Tritium fuel cycle and tritium containment and cleanup system representative of projected power reactor systems.
- Moderate length DT burn (~ tens of seconds); models reactor burn
- Low plant factor but high duty cycle.
- Adequate refueling and impurity control.
- Instrumentation and control system.
- Designed for operation and maintenance in a radiation environment.
- Cooled shield and capability to demonstrate heat removal and breeding in modular tests.
- Cost: ~ $400M in FY 1978 dollars.

5. The Fusion Engineering Research Facility/Engineering Test Reactor (FERF/ETR) is a driven low Q device which uses existing physics but provides major engineering extrapolation. Its objectives and characteristics are:

- Reactor level wall loading for engineering testing of materials and components to commercial plant goal fluences.
- High availability
- Large volume & flexible access for materials testing
- Qualify materials for commercial plants and provide fusion environment verification for the DEMO
- Known physics (TCT, Classical Mirror, etc.)
- Superconducting Magnets for Tokamaks and Mirrors; possibly non-superconducting for other concepts, e.g., theta pinch.
- 50-500 MW electrical power consumption off line to drive plasma
- Provides for extensive testing of blanket modules, neutral beams, vacuum systems, and other engineering features
- Demonstrate tritium breeding in modules
- Tritium fuel cycle and containment/cleanup systems
- Reactor maintenance system required
- Could provide space for testing fusion/fission blankets
- Cost \$500M

6. The Large Hydrogen Experiment (LHX) is a device which comes after proof of principal tests but before the PEPR/ITR step. In the tokamak program Doublet III and TFTR fit in this category. MX and the Large Staged Scyllac also are in this category. It is possible if physics results are unfavorable, to require more than one LHX. LHX would have the following general features:

- Long pulses compared to confinement time
- S/C magnets (except TFTR and High Beta)
- Plasma size is scaleable to EPR-I
- Refueling to maintain density would be demonstrated
- A few DT shots could be carried out to study alpha heating effects.
- Prototype I&C system except for burn dynamics
- Impurity control problems would be defined and solutions explored
- High power heating would allow an approach to reactor level plasmas
- Cost ~ 200M for tokamaks

  ~ 100M for alternate concepts

7. The Tokamak Fusion Test Reactor (TFTR) is the largest currently approved experiment in the fusion program. Its characteristics are:

Objectives

- DT burning, 3 x 10^{18} n/pulse
- Reactor level power densities
- 1.7M plasma diameter
- 20 MW neutral beam injection
- Hydrogen operation June 1981; D&T June 1982
- An upgraded TFTR might incorporate higher plasma current, additional heating capability and longer pulses

Specific Characteristics

- 5-10 keV; 10^{14} cm^{-3} density
- $n\tau = 10^{13}$-10^{14} cm^{-3}sec
- 2.5 MA plasma current
- 5 T toroidal field
- 20 MW, 120 keV D^{o}, .5 sec pulse duration neutral beams
- Vacuum chamber 2.7m major radius; 1.1m minor radius
- Cost ~ 230M

8. The Blanket and Shield Facility (or facilities) must answer the following blanket and shield technology questions:

- Structural adequacy of blanket and first wall by prototype testing
- Test thermal/hydraulic performance
- Test capability of design to accommodate safety/off-normal conditions
- Demonstrate vacuum integrity and remote maintenance operations
- Test neutronic design tools and data
- Verify neutronic performance of prototype designs (Breeding, shielding, effectiveness, etc.)
- Verify design solutions to control neutron streaming
- Verify design solutions to achieve magnetic flux penetration and electromagnetic compatability with plasma support systems.

- Timing
  - The last four items must be completed in time to support any major DT facility
  - Mechanical verification is required to support any facility with EPR or FERF like objectives
- Cost
  - Neutronics requirements of ITR or EPR-I can probably be satisfied by existing facilities. Minor costs for modification are included in the operating budget.
  - A facility to test thermal/hydraulic and mechanical/electrical performance of EPR and DEMO blankets could be a major line item depending on the selected coolants. Cost would range from 25M to 50M.
  - For the purpose of estimating program costs 50M total pace funding is used. Expenditure begins in FY 80 and continues thru FY 85.

9. The Tritium R&D Facility (or facilities) is required to demonstrate safe/economic handling of the large quantities of tritium required for DT fusion power plants. It must resolve the following questions.

- Test features of D&T fuel cycle including:
  - Pumping of hydrogen isotopes and impurities
  - Transfer from pulsed pumping systems to constant pressure resevoir
  - Removal of nonhydrogen impurities
  - Isotope separation
  - Storage
  - Supply to beams and fueling systems
  - Accountability systems
  - Containment materials
- Test large scale containment and cleanup systems
- Demonstrate techniques for extraction of tritium from blankets
  - Extract T from Li, molten salt, solid Li compounds
  - Purify, condition and feed to fuel cycle system
- Timing: The fuel cycle and containment/cleanup systems will be required to support any major DT burning facility. Blanket extraction will be required for the EPR.
- Cost: For near term DT reactors (PEPR/ITR or ETR/FERF) program needs can probably be satisfied in small facilities funded within the operating budget. These facilities plus the actual experience of building reactors could conceivably satisfy all needs but the importance of processing and confining tritium is sufficient so that separate dedicated facilities are provided to support EPR and DEMO. A total PACE cost of 50M is assumed. It is spent in logic III FY 79 through FY 84.

10. A Superconducting Magnet Test Facility(s) will be required to test superconducting magnets for most confinement approaches. Early facilities to test medium scale toroidal magnet systems and pulsed poloidal coils will be funded out of the operating budget. The Large Coil Project is designed to meet these needs for the PEPR/ITR and EPR-I class of reactors. For planning purposes an additional, larger facility to test magnet systems and components for EPR-II/DEMO is assumed later in the program. Its cost is estimated to be 50M and in Logic III Reference Option it will be constructed from FY 82 thru FY 84.

11. The <u>Rotating Target Neutron Source (RTNS)</u> is a near term materials test facility with the following characteristics:

- Two neutron sources
- 14 MeV neutrons
- 1 cc irradiation volume at flux of 2×10^{13} n/cm^2-sec
- February 1978 operational
- Cost ~ \$5M

12. The <u>Intense Neutron Source (INS)</u> is a high flux neutron source with the following features:

- Two neutron sources
  - Source strength = 10^{15}n/sec continuous
  - Max flux = 1.2×10^{14}n/cm^{2}sec
- 14 MeV neutrons
- Few cc's test volume
- \$25M cost
- January 1981 operational

13. The <u>High Flux Neutron Source (HFNS)</u> would have the capability to produce very high fluxes over volumes large compared to the other near term sources. Its objectives are:

- Maximum flux = 10^{15}n/cm^{2}sec
- At least 1000 CC of test volume at a flux of 5×10^{13}n/cm^{2}sec
- Flexible experimental facilities
- Operation in 1982 to 1983
- Cost ~ \$75M

14. Heading Technology Test Facility will be required to support tokamak, mirror and alternate concept programs. In the early phases of the program, neutral beam and alternate heating test stands are constructed out of the operating budget. To support EPR and DEMO it may be necessary to construct a major facility aimed at meeting all future development requirements. For planning purposes this advanced plasma heating test facility is assumed to cost $30M. In Logic III, Reference Option its construction is initiated in FY 83 and completed in FY 85. Its features include:

- Power supplies to drive at least 1 unit of a DEMO heating device
- Pumping system and cryogenic systems to support large neutral beam modules
- Diagnostics and control systems typical of that to be used in a reactor.
- Other facilities, funded from the operating budget include:
  - 150 keV neutral beam test stand, Oct. 1976
  - 200 keV High Voltage Test Stand, July 1977

15. Plasma Maintenance and Control Facilities will be needed to test refueling and impurity control techniques. Early in the program this work can be carried out in close coordination with confinement experiments and small test stands (funding would be included in the operating budget). Early physics results (available by 1979) will dictate the complexity of development tasks in these areas. It is possible that major test stands will be needed to fully develop the components required to carry out these functions for EPR's and DEMO's. Funding for these test stands is assumed to total \$15M and will be spent in 2 FY intervals ending in FY 82 and FY 87. Approximate timing is as follows:

	Start Operation
Plasma Maintenance and Control Facility for EPR Needs	1982
DEMO Plasma Maintenance and Control Facility	1987

16. A Vacuum Technology Testing Facility(ies) will be required to develop reactor type vacuum pumps, valves, seals , leak detectors, etc., for all fusion concepts. In the near term an attempt is made to use existing facilities with modifications and small test stands to support program needs (funded out of operating budget). For EPR and DEMO the nature of components may be such that new facilities would be required. For planning purposes it is assumed that these facilities will cost ~ \$15M and will be built in two FY intervals ending in FY 82 and FY 87. Approximate operation dates for these facilities is:

	Start Operation
Vacuum System Testing Facility for EPR	1982
Vacuum Component/System Test Facility for DEMO	1987

17. _Supporting Test Facilities_ will be needed to support any of the approaches to fusion power as the program progresses to EPR's and DEMO. A general category has been defined and a PACE budget of $100M included in the Logic III Reference Option (see table III-8). The types of things that might be included are direct conversion test stands, control system simulators, and large computing facilities. Before deciding to go ahead with any specific facility or test stand maximum potential of existing facilities (with possible modifications) will be determined. For costing purposes these facilities are constructed over a 9 year period ending in FY 1988.

V. ROLL-BACK PROGRAM ELEMENTS

In the preceeding sections the primary planning approach may be described as "roll-forward," i.e., the current program is considered and, from that consideration, the nature and timing of the next step is determined. A successful fusion power R&D program requires, in addition, a "roll-back" approach in which the nature of the desired end-product, a Fusion Power Demonstration Reactor that extrapolates readily to commercial reactors, is defined in detail and in which the physics and engineering tests required for a DEMO are identified and programs established to provide the required tests. This "roll-back" approach is discussed in this section. Clearly both "roll-forward" and "roll-back" approaches must both be used and be complementary for a successful fusion R&D program.

A. Major Program Elements

In order to build a Fusion Power Demonstration Reactor of any type, certain physics understanding must be demonstrated and certain technological subsystems must be developed. These activities may be categorized as "Major Program Elements." Figure V-1 lists twenty-one Major Program Elements identifiable at this time. Inspection of Figure V-1 suggests that there are two basic classes of Major Program Elements; physics and engineering/technology. Elements I-IV are basically Physics Elements and the remainder are

Figure V-1

Major Program Elements
for all Concepts

Physics

I. Scaling

II. Impurity Control

III. Beta Limits

IV. DT Burn Dynamics

Engineering/Technology

V. Plasma Maintenance and Control

VI. Heating Technology

VII. Superconducting Magnets

VIII. Pulsed Energy Systems

IX. Blanket and Shield

X. Tritium Processing and Control

XI. Electrical Subsystems

XII. Power Handling

XIII. Plant Availability

XIV. Instrumentation and Control

XV. Plant Maintenance

XVI. Vacuum Technology

XVII. Materials

XVIII. Balance of Plant

XIX. Systems Integration

XX. Environment and Safety

XXI. Economics

basically engineering/technology elements. There are both explicit and implicit relationships among these "Elements." Overall technological and economic outlook is determined by the interrelated progress of each Element towards meeting the needs of a fusion DEMO. Tests of the critical physics and/or the technology of the Elements may be made individually in small test facilities and/or collectively in larger facilities. These tests can be described as falling into four classes of tests as follows:

1. Early Tests
2. High Confidence Level Tests
3. Definitive Tests
4. Full Scale DEMO Prototype Tests

Gross program progress may be measured and described in the above terms for each fusion concept. Early tests along with theoretical models provide the definition of the problems for the progress of each program element. High Confidence Level tests are conducted via model and machine experiments. Definitive tests provide the understanding of scaling laws necessary for DEMO design. Full scale DEMO prototype tests demonstrate the readiness for DEMO application.

Major facilities (described in Section III-E) are justified in part, by stating the level of test they will provide for each Major Program Element. Major Program Element tests, at different levels of confidence, are performed at different times depending on the option taken and the fusion concept assumed for DEMO. Figure V-2 is a flow chart showing the times at which various classes of tests

Figure V-2

TOKAMAK MAJOR PROGRAM ELEMENTS FLOW CHART
LOGIC III REFERENCE OPTION

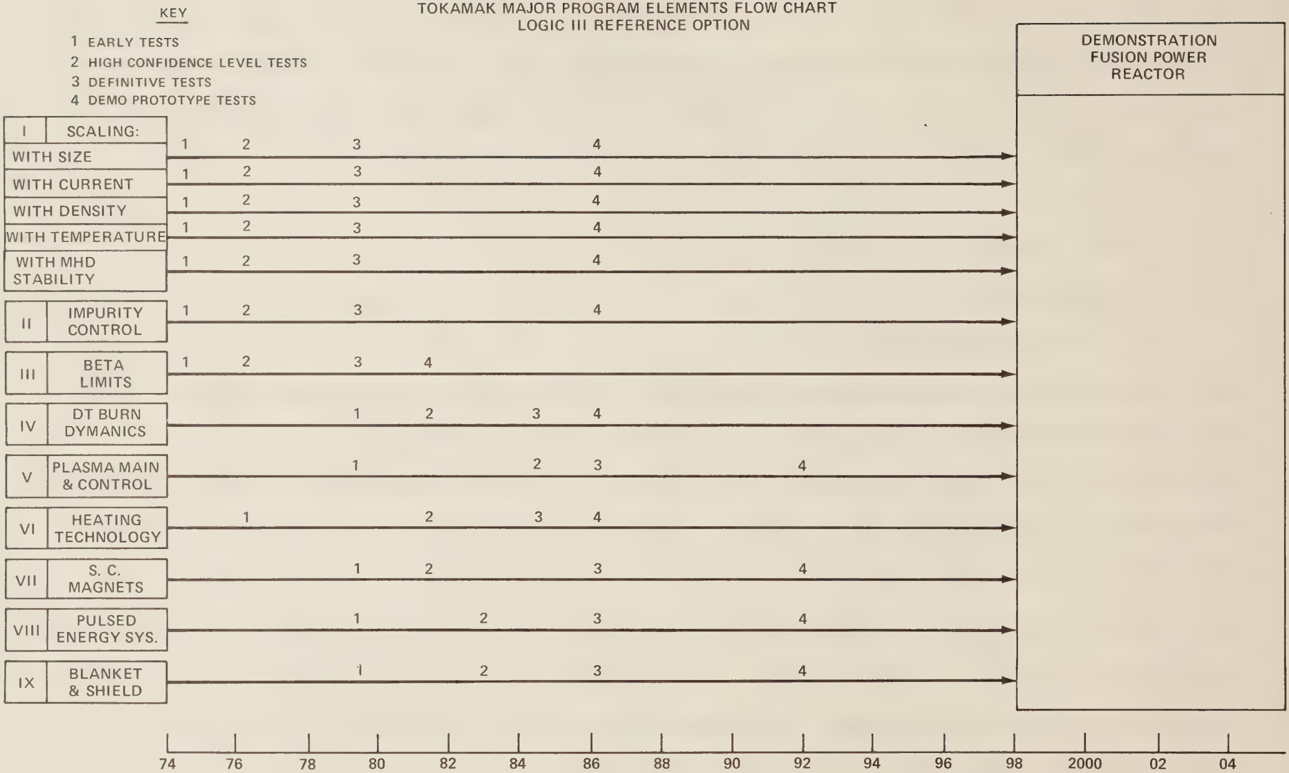
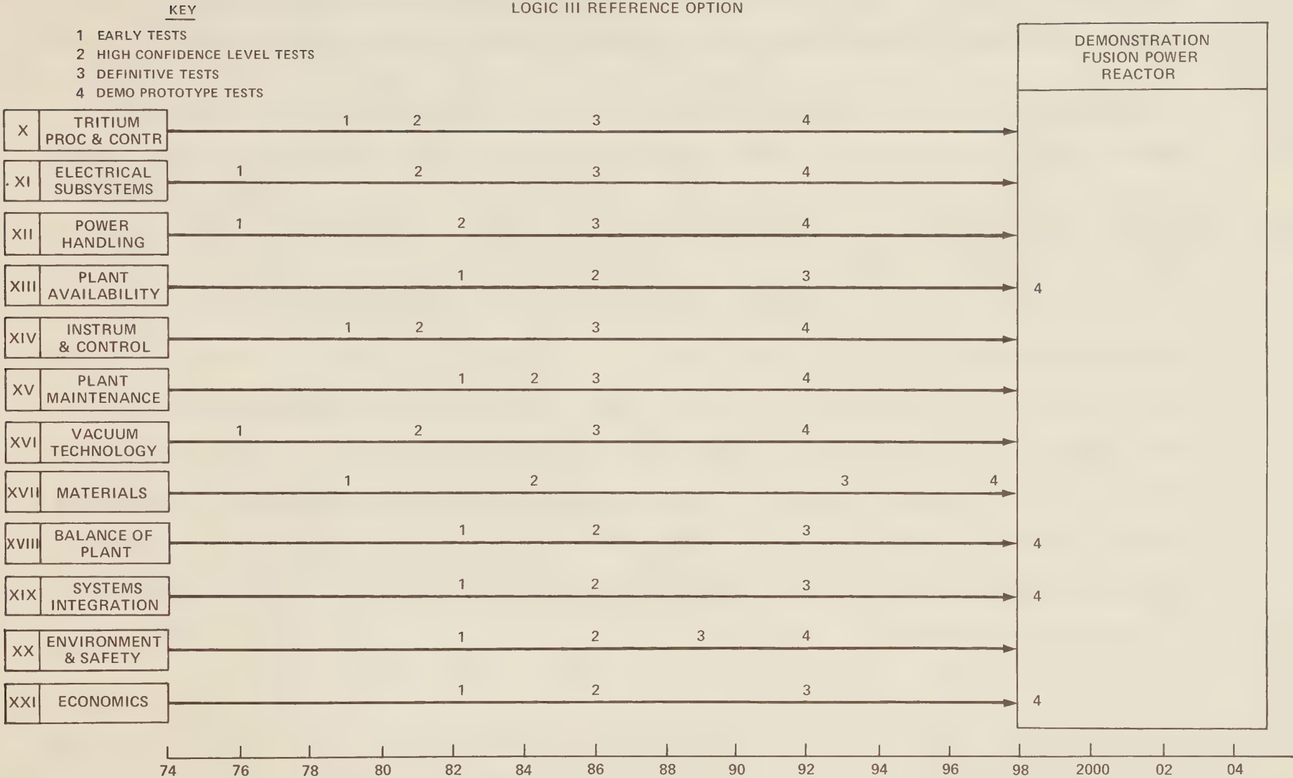


Figure V-2 - continued

TOKAMAK MAJOR PROGRAM ELEMENTS FLOW CHART
LOGIC III REFERENCE OPTION



are expected in the areas of the twenty-one program elements for the Logic III Reference Option program for the tokamak concept. Each of the horizontal arrows represents the progress of a Major Program Element. The numbers in parentheses indicate the various classes of tests expected.

The twenty-one Major Program Elements are discussed in some detail in the following text to provide further insight into this planning method. The scope of the discussion covers all the fusion concepts but more information is provided on the tokamak concept because of the current preeminence of this approach. The elements are general enough to cover all the fusion concepts. The Critical Physics and Engineering Parameters and the schedule for all the assessments were discussed in Section III.B.

ELEMENT I: SCALING

Scaling in fusion systems refers to the physical laws relating the plasma confinement time to device size, plasma current, plasma density, magnetic field, plasma temperature, pulse length, MHD stability, etc. In the tokamak area, for example, it is expected that larger devices will be able to carry more current, resulting in reduced losses and higher temperatures. The determination of scaling laws by theory and experimentation for reactor grade plasmas is a key factor in determining the eventual economics of fusion reactors.

The plasma scaling with size, current, density, temperature, and MHD stability is discussed below for all fusion concepts. There is more information on the tokamak concept because of the level of progress compared to mirror and other alternate concepts. An assessment of the implications for DEMO scaling with plasma size, current, density, temperature and MHD stability for tokamaks will be made in CY 1979.

A. Scaling with Size

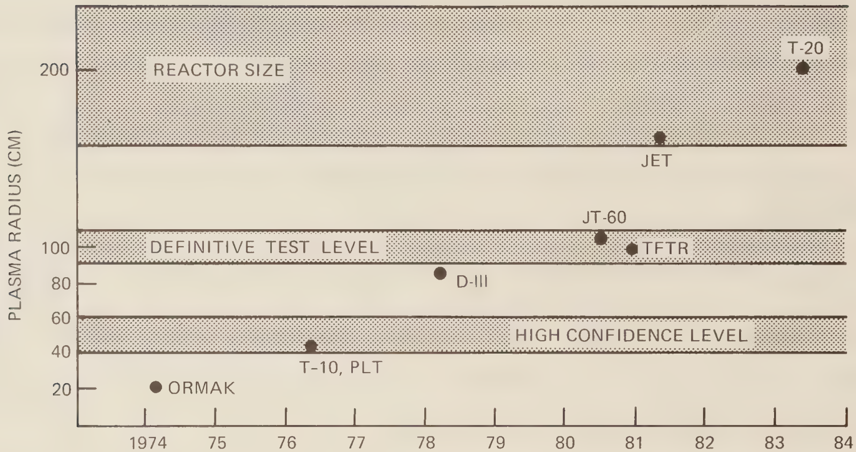
Information on scaling with size is obtained through experimental tests on a series of successively larger devices. For reactor level tests, a device with at least a 1.5-m minor radius is required for tokamaks. Early tests have come from ST and ORMAK; High Confidence Level Tests will be available from PLT, D-III, and T-10; Definitive Tests will come from TFTR; and DEMO Prototype Tests will come from PEPR/ITR. A chart showing size scaling is provided in Figure V-3.

For the mirror concept, scaling of losses due to microinstabilities with plasma radius R_p and length between mirrors L measured in gyroradii ρ_i must be established. MX should do this up to $R_p/\rho_i \sim 13$, $L/\rho_i \sim 100$, i.e., High Confidence Level. Definitive tests will include $R_p/\rho_i \sim 50$, $L/\rho_i \sim 200$. For the toroidal theta pinch, scaling of m=1 and m=2 growth rates with major radius and high beta stellarator parameters must be established.

B. Scaling with Current

Information on tokamak scaling with current, like information on size scaling, will be obtained through tests on a series of successively larger devices. For DEMO level tests, plasma currents of approximately

Figure V-3



CONFINEMENT SCALING WITH SIZE

	Plasma Radius (cm)	Initiate Experiments	Evaluate Results
1. ORMAK	23.0	1972	1974
2. T-10 (USSR)	36.5	July 1975	July 1976
3. PLT	45.0	Dec. 1975	Sept. 1976
4. TFTR	90.0	1981	1982
5. JET (Europe)	125/200	1981	1982
6. DOUBLET III	45/150	1978	1979
7. JT-60 (Japan)	100	1979	1980
8. T-20 (USSR)	200	1982	1983

10 megaamperes are required for tokamaks. Early tests came from ORMAK and TFR; High Confidence Level tests will come from PLT and T-10; Definitive Tests will be available from D-III and TFTR; and DEMO Prototype tests will come from PEPR/ITR. A chart showing current scaling is provided as Figure V-4.

C. Scaling with Density

Information on scaling with density may lead to consideration of two possible types of tokamak reactor systems. The first is the conventional tokamak reactor concept which utilizes moderate magnetic field strengths and plasma densities of about $10^{14} cm^{-3}$. The second is a possible high-field reactor which would operate with densities of close to $10^{15} cm^{-3}$. If a significant reduction in energy transport and/or a significant reduction of impurities can be effected through operation at high densities then the possible disadvantages of the required high magnetic fields and possible difficulties with heating and refueling may be offset.

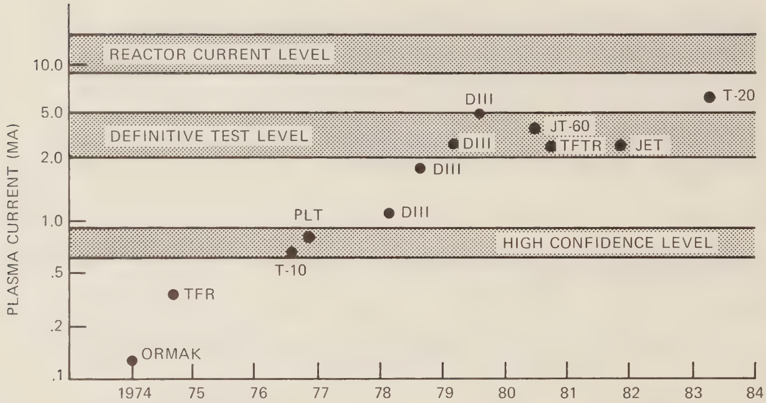
Early tests of density scaling have come from ORMAK and from Alcator A; High Confidence Level tests will come from PLT; Definitive Tests will be available from D-III for conventional design and from Alcator C for high field designs; and DEMO Prototype tests will come from PEPR/ITR. A chart showing density scaling is provided as Figure V-5.

D. Scaling with Temperature

For DEMO level plasmas, tests of plasma transport in the "trapped particle regime" will be required since reactors with plasma temperatures of 10 keV or greater will likely give plasma conditions in this regime. Early tests of temperature scaling for tokamaks have come from ORMAK and TFR; High

Figure V-4

TOKAMAK SCALING TO HIGHER PLASMA CURRENT

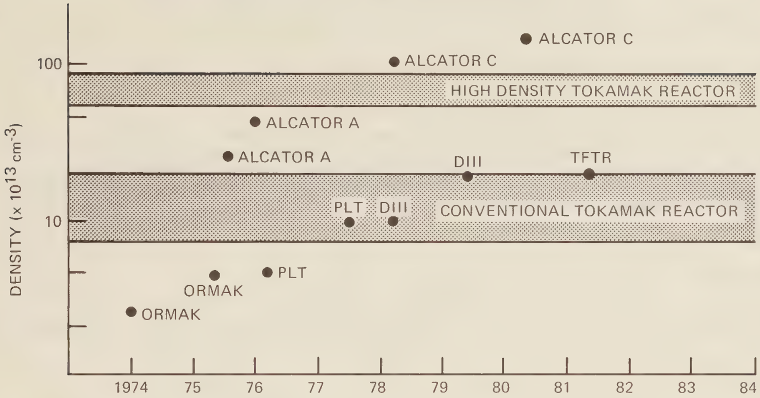


CONFINEMENT SCALING WITH PLASMA CURRENT

	Current (kA)	Initiate Experiments	Evaluate Results
1. ORMAK	200	1975	1976
2. TFR (France)	400	1974	1975
3. T-10 (USSR)	400 600	1975	1976
4. PLT	400 800	1976 1978	1976 1979
5. DOUBLET III	2000 3000 5000	1978 1979 1979	1979 1979 1980
6. TFTR	2500	1981	1982
7. JET (Europe)	4800	1980	1981
8. JT-60 (Japan)	3300	1979	1980
9. T-20 (USSR)	6000	1982	1983

Figure V-5

TOKAMAK SCALING TO HIGHER DENSITY



CONFINEMENT SCALING WITH DENSITY

	Field (kG)	Density (x 10^{13} cm^{-3})	Initiate Experiments	Evaluate Results
1. TFR (France)	60	12	1974	1975
2. ORMAK	18	4	1973	1974
	25	10	1975	1975
	30	12	1976	1976
3. ALCATOR A	50	20	1975	1975-1976
	70	60		
	90	60		
4. PLT	35	5	1976	1976
	50	10		
5. FRASCATI TORUS (Italy)	100	50	1976	1977
6. ALCATOR C	100	50	1977	1978
	120	70		1979
	140	100		1980
7. ORMAK UPGRADE	40	14	1978	1979
8. DOUBLET III	26	20	1978	1979
9. TFTR	50	20	1981	1982

Confidence Level Tests will be available from PLT and Doublet III; Definitive Tests will come from PLT, ORMAK, and Doublet III Upgrades, and TFTR; and DEMO Prototype Tests will be obtained from PEPR/ITR. A chart showing temperature scaling is provided as Figure V-6.

For the mirror concept, scaling of the density-confinement time product ($n\tau$) with temperature must be demonstrated up to DEMO values. Theory predicts $n\tau$ is proportional to $T_i^{3/2}$; this has been verified in 2XII-B up to $T_i \sim 13$ keV. MX will provide a High Confidence Level Test with $T_i \sim 50$ keV and PEPR/ITR will be definitive.

For the toroidal theta pinch concept, shock compression must produce ignition temperatures but with a ratio of temperature to B^2 which avoids the m=2 instability.

E. Scaling with MHD Stability

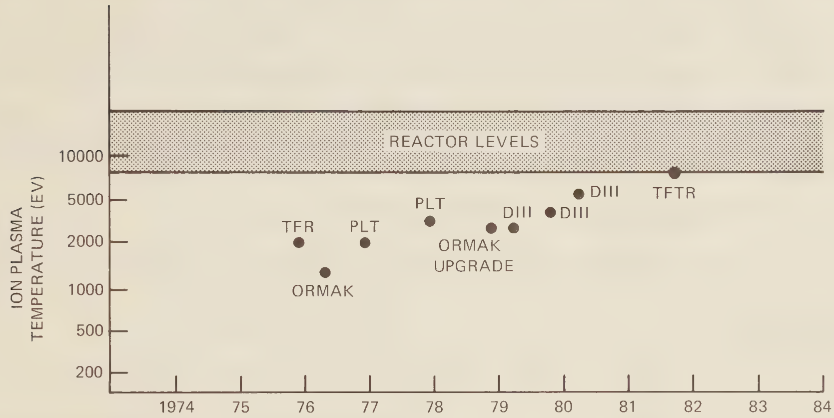
Scaling information is required on plasma equilibrium and stability to macroscopic MHD modes (at large aspect ratios and on relevant MHD time scales for the toroidal theta pinch and other alternate concepts) and plasma confinement in the presence of MHD transport. Early tests were performed with ST and ATC for the tokamak concept; High Confidence Level Tests will be conducted with PLT and ORMAK Upgrade; Definitive Tests will be achieved with PDX, D-III and TFTR; PEPR/ITR will provide Demo Prototype Tests.

ELEMENT II: IMPURITY CONTROL

Adequate means for controlling impurity concentration is essential to tokamak fusion systems. Small amounts of heavy element impurities can lead to unacceptably large plasma energy loss during a burn.

Figure V-6

TOKAMAK SCALING TO HIGHER TEMPERATURES



CONFINEMENT SCALING WITH TEMPERATURE

	El. Temp.	Ion Temp.	Initiate Experiments	Evaluate Results
1. TFR (France)	3000	2000	1976	1976
2. ORMAK	1000	1500	1975	1976
3. PLT	2000	2000	1976	1977
	3000	3000	1977	1977
4. ORMAK UPGRADE	2000	2000	1979	1979
5. DOUBLET III	2000	2000	1978	1979
	3000	3000	1979	1980
	5000	5000	1980	1981
6. TFTR	5000	5000	1981	1982

A number of possible impurity control techniques are being tested to allow long burns. These are divertors, gas flow, wall material variations including low-Z coatings, and honey-comb wall structures. It is also possible that the plasma can be controlled to expel impurities in which case there may not be a need for external impurity measures. Early tests have come from ATC and Alcator A; High Confidence Level Tests will come from PLT, ISX, and DITE (in the U.K.); Definitive Tests will be available from PDX; and DEMO Prototype Tests will come from TFTR and PEPR/ITR. A table showing tests of impurity control is provided as Figure V-7.

An assessment of how complex the impurity control techniques should be will be made in CY 1979.

ELEMENT III: BETA LIMITS

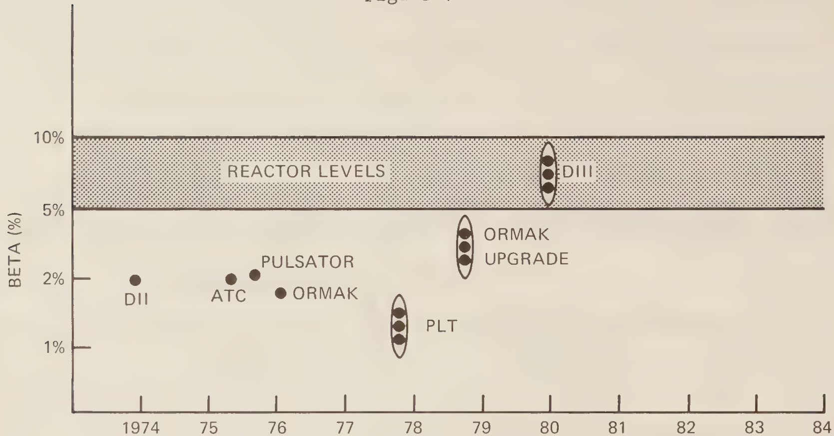
The limiting beta (ratio of plasma to magnetic field pressure) in tokamaks is an important element in their economics for power reactors. Beta's of 5-10% are expected to be required for an economic system. A particularly important part of the tokamak program is to test the high beta limit of non-circular section devices and of rapidly heated tokamaks in general. Early tests have come from D-II; High Confidence Level Tests will be available with PLT; Definitive Level Tests will come from ORMAK Upgrade, PDX and D-III; and DEMO Prototype Tests will come from TFTR and PEPR/ITR. A chart showing tests of plasma beta is provided as Figure V-8. An assessment of the magnitude of the plasma beta for DEMO will be provided in CY 1979.

Figure V-7

IMPURITY CONTROL AND BOUNDARY EFFECTS

	Method	Initiate Experiments	Evaluate Results
1. ORMAK	Gold walls	1975	1975
2. ALCATOR	Wall prep.	1974	1975
3. PLT	Disch. cleaning	1977	1978
4. DITE (U.K.)	Tor. Div.	1976	1977
5. ISX	Gas Flow	1977	1978
	Walls	1978	1979
6. PDX	Pol. Div.	1978	1979
7. MACROTOR	Disch. Cleaning	1976	1977
	Vapor Deposition	1977	1977

Figure V-8



Tests of Plasma Beta

	Beta (%)	Initiate Experiments	Evaluate Results
1. DOUBLET II	2%	1972	1974
2. ORMAK UPGRADE	2%-4%	1979	1979
3. DOUBLET III	5%-10%	1980	1980
4. PLT	1%-2%	1977	1978
5. ATC	2%	1975	1975
6. ORMAK	1.5%	1976	1976
7. PULSATOR	1.6%	1975	1975

Mirror confinement and power improve with β. There is preliminary evidence in 2XIIB that values of $\beta \gtrsim 1$ can be achieved. This will be investigated in larger devices; MX should be a High Confidence Level Test and PEPR/ITR should be definitive. The beta values regularly achieved in theta pinches are in the range 0.6-1.0.

ELEMENT IV: DT BURN DYNAMICS

The burning of DT plasmas with the resultant generation of energetic alpha particles in the plasma introduces new physics problems. The early test of this physics for tokamaks will come from simulations in PLT and ORMAK Upgrade; High Confidence Level Tests will be available from TFTR; Definitive Tests will come from the TFTR Upgrade; and DEMO Prototype Tests will be obtained from PEPR/ITR. This Major Program Element is inclusive of startup and burn termination associated physics.

ELEMENT V: PLASMA MAINTENANCE AND CONTROL

All plasma maintenance and control components and systems that are required for achievement of the desired DEMO plasma are combined under this Major Program Element. Hence, it includes the development of refueling, impurity control and startup and burn termination related components and systems. The requirements will be available from the developments in the Major Program Elements I-IV.

Reactor refueling is required for all fusion approaches and only recently has been determined as an engineering/technology needing early verification. For tokamaks, several approaches may be available, depending on the operating characteristics of the facility (particularly duty factors). Mirrors can be refueled by neutral beam injection and other Alternate Concepts may have less rigid requirements than tokamaks. Presently, the types of refueling expected for tokamaks are: neutral gas blankets, pellets, and neutral beams. Early tests of the physics will come from ORMAK, PLT, and ORMAK Upgrade; High Confidence Level Tests will be available from TFTR; Definitive Tests and DEMO Prototype tests will have to be performed with PEPR/ITR and EPR, respectively.

An assessment of the technology of plasma refueling and impurity control will be achieved in CY 1979. For toroidal theta pinch concept, methods will be assessed for preparing ~ 1 keV plasma for adiabatic compression to ignition.

ELEMENT VI: HEATING TECHNOLOGY

Heating methods for tokamaks currently are based on neutral beams and ohmic heating. Other possible heating methods include adiabatic compression, radiofrequency heating and magnetic implosion. Neutral

beams are regarded now as the most likely method for auxiliary tokamak plasma heating and are judged on the basis of: energy, efficiency, and power. Optimistic values of each of these criteria are presumed to be required for the demonstration of fusion power economics although there may be some relaxation based on reactor Q and ignition conditions. For tokamaks and mirrors, High Confidence Level Tests are expected before the end of this decade. DEMO Prototype tests are essential by 1987 (PEPR/ITR) if the program is to proceed to demonstration of fusion economics before the end of the century.

Mirror heating and refueling are accomplished with neutral beam systems. Beam systems being developed for TFTR, D-III and MX will provide High Confidence Level Tests. PEPR/ITR would be definitive.

An assessment of the technology of all heating methods will be carried out in CY 1979.

ELEMENT VII: SUPERCONDUCTING MAGNETS

Superconducting magnets will be used for confinement in most fusion reactor concepts and probably for energy storage and transfer also. Pulsed magnet systems are covered under the next Major Program

Element; thus, only large steady state coils are covered here. The major criteria for large superconducting magnet sets are maximum current density, maximum field at the conductor, strain limitations and structural requirements. Early and High Confidence Level Tests of these criteria must be performed on an accelerated schedule in order that DEMO scale tests can be achieved on the EPR in the Logic III Reference Option. However, the economics will have to be reconfirmed with the DEMO as the superconducting magnets will represent a large fraction of the thermonuclear island cost. An assessment of the technology of high toroidal field large magnets will be achieved in CY 1979. Some data are provided on tokamak scaling with magnetic field in Section III.D, Figure III-9.

ELEMENT VIII: PULSED ENERGY SYSTEMS

Very large pulsed energy systems will be required in fusion reactors. These are ohmic heating supplies in tokamaks and main compression supplies in high β devices. These supplies must be made reliable, efficient and inexpensive. Systems under consideration include large pulsed superconducting coils which are technically very different from the steady state magnets for confinement, pulsed homopolar machines and inductive storage/switching systems. Pulsed superconducting coils must be developed for the plasma driving systems of net power producing tokamak reactors. Energy transfer and storage devices which match the requirements of the pulsed coils must be developed in parallel. Definitive tests will be achieved with PEPR/ITR. DEMO Prototype Tests will come from EPR. An assessment of the technology of matched superconducting pulsed coil and energy storage systems will be achieved in CY 1979.

ELEMENT IX: BLANKET AND SHIELD

Fusion reactor blankets require substantial development efforts in neutronics, coolant technology, mechanics, heat transfer, fabrication, assembly, etc. An assessment of the cooling and mechanical performance requirements of the first wall and the integrity of a low-Z coating will be achieved in CY 1979.

Blanket and shield technologies must be demonstrated in PEPR/ITR and EPR or any large high duty cycle fusion facility. For tokamaks, the EPR is the DEMO Prototype Test. Fusion blankets, because of the required geometrical factors, are expected to be a challenging developmental effort. For fusion-fission coupling these factors with additional fission type requirements will certainly make the design more complex. This technology will depend on the extent to which fusion-fission concepts are developed.

ELEMENT X: TRITIUM PROCESSING AND CONTROL

Since the present fusion power R&D program is based on the D-Li-T fuel cycle, tritium processing and control technologies must be demonstrated as early as possible. Any EPR certainly will require fully engineered tritium handling systems. An assessment of the technologies of tritium fuel cycle will be achieved in CY 1979.

ELEMENT XI: ELECTRICAL SUBSYSTEMS

Fusion requires a high voltage-high power technology and demonstration of the electrical subsystems must pace the program schedule. The requirements for these subsystems are a strong function of the physics results and confinement approach. Low Q devices, characterized by high circulating power, represent

one extreme while high Q ignition devices represent the other. The problem of duty cycle further complicates the development effort. Considering the Logic III Reference Option, one would suspect that high voltage, high power, modest duty cycle electrical systems will be required for a Tokamak PEPR/ITR. However, should any FERF/ETR be constructed, steady state, high voltage, high power subsystems would have to be demonstrated to the DEMO scale by the middle of the 80's. An assessment of power supply technology will be achieved in CY 79.

ELEMENT XII: POWER HANDLING

The importance of power handling is demonstrated in the technological and economic requirements for fusion energy. Fusion reactors as power amplifiers require input power for multiplication by the fusion reaction. The road to achievement of net power in an EPR will be through efficient power handling in all fusion systems. The net power production will be determined not only by the fusion power generated but also by the power requirements of the plasma confinement- heating system and the power conversion system. Hence, in addition to the development of other program elements, the development of direct converters for neutral beam injectors and mirror reactors and Q enhancement of mirror concepts will be carried out in an orderly and responsive fashion.

For Q values greater than ~ 2, investigation of "non-standard" mirror confinement schemes such as field reversal, stoppering, etc. is required. Several such ideas are being pursued in 2XII-B and other smaller

facilities. MX with its large neutral beam capability will continue investigation of the most promising concepts to the point of High Confidence Level tests.

An assessment of the direct converter technology will be achieved in CY 79.

ELEMENT XIII: PLANT AVAILABILITY

Plant availability is a prime value measure of the economics of any integrated system. A high availability will have to be proven at the reactor scale by the DEMO and certainly be demonstrated at the definitive level by an EPR class of machine. High availability also is desireable for precursor facilities (e.g., PEPR/ITR, MX, etc.) as more physics and engineering tests can be made per operating dollar. The reliability level of reactor components and systems obviously will determine the achievement of a high availability.

ELEMENT XIV: INSTRUMENTATION AND CONTROL

Instrumentation and control elements of fusion power plants will be defined as the operating characteristics of these facilities are determined. Clearly, however, this element becomes more and more critical as the program progresses from devices which are primarily experimental physics devices to devices whose primary purpose is to generate energy. Early tests of I&C concepts should be tested in the present generation of devices. High Confidence Level Tests should be incorporated in PEPR/ITR. Complete DEMO Prototype tests must be performed by EPR for the I&C components and systems including plasma diagnostic equipment. The economics of such systems would be addressed in DEMO.

ELEMENT XV: PLANT MAINTENANCE

Plant maintenance will offer challenging problems for fusion plants because of their configuration and, perhaps, size. It is clear that remote maintenance will be a requirement and will have to be adequately demonstrated in an orderly sequence of fusion facilities. Remote maintenance and assembly of reactor components (including first wall, blanket and beams) will be necessary with D-T operation. Reactor scale demonstration will be required by an EPR type of facility, and a scale-up to DEMO and commercial plants must be shown to be feasible. An assessment of the technology of remote maintenance and assembly will be achieved in CY 79.

ELEMENT XVI: VACUUM TECHNOLOGY

The fusion concepts require reliable and inexpensive vacuum systems which must scale to large machines and their radiation environment. Experience has shown that vacuum systems have a significant impact on a machine's availability and therefore must be demonstrated to the DEMO level by an EPR class of machine. It must be noted that the vacuum systems will depend strongly on vessel integrity and vacuum pumps and will be intimately integrated with the fuel cycle. If the reliability is demonstrated by an EPR, it is expected that scaling to a DEMO will be relatively straightforward. An assessment of the toroidal and beam vacuum technology will be achieved in CY 79.

ELEMENT XVII: MATERIALS

The materials requirements for fusion reactors will be developed and will be characterized by specific fusion facilities. Reactor-scale materials performance will be verified in the DEMO but earlier ongoing

radiation environment tests will have specified material, choices and expectations. It is far from clear what specific materials will be used in the DEMO or in commercial reactors. However, the principal focus will be on the development of radiation resistant first wall, blanket and structural materials for commercial reactors which can survive in this unique radiation environment. Materials developed at earlier stages in the program may find application in EPR's and the DEMO. In Section III.B, materials and components testing is discussed with the FERF/ETR Options.

ELEMENT XVIII: BALANCE OF PLANT

The balance of plant requirements are really reserved for DEMO and commercial plants. The balance of plant (BOP) will include all facilities except the (thermo)nuclear island. These facilities will have features similar to those found in fossil and fission plants with the possible exception of thermal storage. The BOP requirements will evolve with the progress of the fusion program towards the DEMO. An EPR will have the most definitive features before the DEMO BOP.

ELEMENT XIX: SYSTEMS INTEGRATION

The systems and subsystems of a fusion system have interface requirements that must be met for system integration. This is critical for success in the design, manufacturing, construction, assembly and operation phases of any facility or machine. The interface demands exist among the components of a subsystem or the subsystems of a system or the systems of an integrated fusion system. The process of

systems integration will be executed in each device of the fusion program. However, the level of complexity will increase beginning with TFTR. The DEMO level systems integration can only be achieved with the DEMO.

ELEMENT XX: ENVIRONMENT AND SAFETY

Environment and safety is included as a program element because the goal of the fusion program is to assure the development and ultimate operation of fusion power reactors with acceptable adverse effects on the environment and with maximum safety for the public. All potential hazards will be identified and necessary safety features, engineered controls and safeguards will be developed in an orderly fashion. The progress towards a safe, reliable and environmentally acceptable fusion industry will be achieved with systematic analysis and assessment of the environment and safety implications of each fusion device. This progress will have the early applications with TFTR. The DEMO level assessment will be achieved with the EPR.

ELEMENT XXI: ECONOMICS

Economics is a measure of the competitiveness of fusion energy with other energy options. A safe, reliable and environmentally acceptable fusion industry also will have to be economically attractive. Because of the present status of the fusion program, there are large uncertainties in the fusion economics.

VI. BUDGET SUMMARY

Total program costs by Fiscal Year are shown as follows:

	Summary
LOGIC II	Figure VI-1
LOGIC III	Figure VI-2
LOGIC IV	Figure VI-3
LOGIC V	Figure VI-4

A summary of the fiscal data is shown below:

$M

LOGIC	I	II	III	IV	V
TOKAMAK PACE		2630	2630	2630	4140
ENG. FAC. PACE		875	875	1050	1710
ALT. CONC. PACE		1600	2000	2000	4940
OPERATIONS		10120	9017	8260	8490
EQUIPMENT		987	992	826	849
TOTAL		16212	15514	14766	20129

Figure VI-1 PROGRAM COSTS BY YEAR FOR LOGIC II REFERENCE OPTION ($M)

	FY76	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	FY87	FY88	FY89	FY90	FY91
TOKAMAK PACE	20	80	95	35	15	35	35	15	40	60	100	100	60	40	0	40
TFTR	20	80	95	35	15	35	35	15	0	0	0	0	0	0	0	0
PEPR/ITR	0	0	0	0	0	0	0	0	40	60	100	100	60	40	0	0
EPR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40
DEMO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ENG. FAC. PACE	2	18	10	10	20	35	56	66	54	25	20	16	44	88	168	163
FERF/ETR	0	0	0	0	0	0	0	0	0	0	0	0	25	75	150	150
HFNS	0	0	0	10	15	20	20	10	0	0	0	0	0	0	0	0
HTTF	0	0	0	0	0	0	0	6	9	0	0	6	9	0	0	0
TF	0	0	0	0	5	10	20	10	5	0	0	0	0	0	0	0
B&S	0	0	0	0	0	5	10	20	10	5	0	0	0	0	0	0
RTNS	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INS	0	15	10	0	0	0	0	0	0	0	0	0	0	0	0	0
PMCTF	0	0	0	0	0	0	3	5	0	0	0	0	0	3	4	0
VTF	0	0	0	0	0	0	3	5	0	0	0	0	0	0	4	3
SMTF	0	0	0	0	0	0	0	0	10	10	10	0	0	0	0	0
Eng. Test. Fac.	0	0	0	0	0	0	0	10	20	10	10	10	10	10	10	10
ALT. CONC. PACE	0	0	0	15	35	35	15	0	0	0	45	105	105	65	60	120
LHX																
MX	0	0	0	15	35	35	15	0	0	0	0	0	0	0	0	0
LSS	0	0	0	0	0	0	0	0	0	0	15	35	35	15	0	0
#3	0	0	0	0	0	0	0	0	0	0	15	35	35	15	0	0
#4	0	0	0	0	0	0	0	0	0	0	15	35	35	15	0	0
PEPR	0	0	0	0	0	0	0	0	0	0	0	0	0	20	60	120
EPR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL PACE	22	98	105	60	70	105	106	81	94	85	165	221	209	193	228	323
OPERATIONS	120	156	180	210	235	255	270	280	290	300	310	320	330	340	350	360
EQUIPMENT	17	20	18	21	24	26	27	28	29	30	31	32	33	34	35	36
TOTAL PROGRAM	159	274	303	291	329	386	403	389	413	415	506	573	572	567	613	719

Figure VI-1 - continued

	FY92	FY93	FY94	FY95	FY96	FY97	FY98	FY99	FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	28yr. Total FY78-2005
TOKAMAK PACE	80	160	240	160	80	40	50	100	200	250	250	200	100	50	2630
TFTR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	230
PEPR/ITR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	400
EPR	80	160	240	160	80	40	0	0	0	0	0	0	0	0	800
DEMO	0	0	0	0	0	0	50	100	200	250	250	200	100	50	1200
ENG. FAC. PACE	75	25	0	0	0	0	0	0	0	0	0	0	0	0	875
FERF/ETR	75	25	0	0	0	0	0	0	0	0	0	0	0	0	500
HFNS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75
HTTF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
TF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
B&S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50
RTNS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
PMCTF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
VTF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
SMTF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
Eng. Test. Fac.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
ALT. CONC. PACE	120	60	20	0	40	80	160	240	160	80	40	0	0	0	1600
LHX															
MX	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
LSS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
#3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PEPR	120	60	20	0	0	0	0	0	0	0	0	0	0	0	400
EPR	0	0	0	0	40	80	160	240	160	80	40	0	0	0	800
TOTAL PACE	275	245	260	160	120	120	210	340	360	330	290	200	100	50	5105
OPERATIONS	370	380	390	400	410	420	430	440	450	460	470	480	490	500	10120
EQUIPMENT	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1013
TOTAL PROGRAM	682	663	689	600	571	582	683	824	855	836	807	728	639	600	16238

Figure VI-2 PROGRAM COSTS BY YEAR FOR THE LOGIC III REFERENCE OPTION ($M)

	FY76	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	FY87	FY88	FY89	FY90
TOKAMAK PACE	20	80	95	50	65	115	140	105	45	15	40	120	240	240	120
TFTR	20	80	95	35	15	35	35	15	0	0	0	0	0	0	0
PEPR/ITR Fac.	0	0	0	15	35	35	15	0	0	0	0	0	0	0	0
PEPR/ITR Dev.	0	0	0	0	15	45	90	90	45	15	0	0	0	0	0
EPR	0	0	0	0	0	0	0	0	0	0	40	120	240	240	120
DEMO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ENG. FAC. PACE	2	18	20	20	45	82	79	60	100	160	172	102	35	0	0
FERF/ETR	0	0	0	0	0	0	0	25	75	150	150	75	25	0	0
HFNS	0	0	10	15	20	20	10	0	0	0	0	0	0	0	0
HTTF	0	0	0	0	0	6	9	0	0	0	6	9	0	0	0
TF	0	0	0	5	10	20	10	5	0	0	0	0	0	0	0
B&S	0	0	0	0	5	10	20	10	5	0	0	0	0	0	0
RTNS	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0
INS	0	15	10	0	0	0	0	0	0	0	0	0	0	0	0
PMCTF	0	0	0	0	0	3	5	0	0	0	3	4	0	0	0
VTF	0	0	0	0	0	3	5	0	0	0	3	4	0	0	0
SMTF	0	0	0	0	0	0	10	10	10	0	0	0	0	0	0
Eng. Test. Fac.	0	0	0	0	10	20	10	10	10	10	10	10	10	0	0
ALT. CONC. PACE	0	0	15	35	35	60	105	105	65	60	120	140	120	140	120
LHX															
MX	0	0	15	35	35	15	0	0	0	0	0	0	0	0	0
LSS	0	0	0	0	0	15	35	35	15	0	0	0	0	0	0
#3	0	0	0	0	0	15	35	35	15	0	0	0	0	0	0
#4	0	0	0	0	0	15	35	35	15	0	0	0	0	0	0
M-PEPR 1	0	0	0	0	0	0	0	0	20	60	120	120	60	20	0
A-PEPR 2.	0	0	0	0	0	0	0	0	0	0	0	20	60	120	120
EPR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL PACE	22	98	130	105	145	257	324	270	210	235	332	362	395	380	240
OPERATIONS	120	183	248	280	327	346	376	390	400	410	420	430	440	450	460
EQUIPMENT	17	23	32	45	55	45	55	55	40	41	42	43	44	45	46
TOTAL PROGRAM	159	304	410	430	527	648	755	715	648	686	794	835	879	875	746

Figure VI-2 - continued

	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98	21yr. Total FY78-98
TOKAMAK PACE	40	60	120	240	360	240	120	60	2630
TFTR	0	0	0	0	0	0	0	0	230
PEPR/ITR Fac.	0	0	0	0	0	0	0	0	100
PEPR/ITR Dev.	0	0	0	0	0	0	0	0	300
EPR	40	0	0	0	0	0	0	0	800
DEMO	0	60	120	240	360	240	120	60	1200
ENG. FAC. PACE	0	0	0	0	0	0	0	0	875
FERF/ETR	0	0	0	0	0	0	0	0	500
HFNS	0	0	0	0	0	0	0	0	75
HTTF	0	0	0	0	0	0	0	0	30
TF	0	0	0	0	0	0	0	0	50
B&S	0	0	0	0	0	0	0	0	50
TRNS	0	0	0	0	0	0	0	0	0
INS	0	0	0	0	0	0	0	0	10
PMCTF	0	0	0	0	0	0	0	0	15
VTF	0	0	0	0	0	0	0	0	15
SMTF	0	0	0	0	0	0	0	0	30
Eng. Test Fac.	0	0	0	0	0	0	0	0	100
ALT. CONC. PACE	100	140	240	240	120	40	0	0	2000
LHX									
MX	0	0	0	0	0	0	0	0	100
LSS	0	0	0	0	0	0	0	0	100
#3	0	0	0	0	0	0	0	0	100
#4	0	0	0	0	0	0	0	0	100
M-PEPR 1	0	0	0	0	0	0	0	0	400
A-PEPR 2	60	20	0	0	0	0	0	0	400
EPR	40	120	240	240	120	40	0	0	800
TOTAL PACE	140	200	360	480	480	280	120	60	5505
OPERATIONS	470	480	490	500	510	520	530	540	9017
EQUIPMENT	47	48	49	50	51	52	53	54	992
TOTAL PROGRAM	657	728	899	1030	1041	852	703	654	15514

Figure VI-3 PROGRAM COSTS BY YEAR FOR LOGIC IV REFERENCE OPTION ($M)

	FY76	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	FY87	FY88	FY89	FY90	FY91	FY92	FY93	15yr. Total FY78-93
TOKAMAK PACE	20	80	95	35	55	105	195	95	120	180	280	180	140	180	360	360	180	60	2630
TFTR	20	80	95	35	15	35	35	15	0	0	0	0	0	0	0	0	0	0	230
PEPR/ITR	0	0	0	0	40	80	160	80	40	0	0	0	0	0	0	0	0	0	400
EPR	0	0	0	0	0	0	0	0	80	180	280	180	80	0	0	0	0	0	800
DEMO	0	0	0	0	0	0	0	0	0	0	0	0	60	180	360	360	180	60	1200
ENG. FAC. PACE	2	18	25	50	102	129	125	140	230	132	87	20	10	0	0	0	0	0	1050
FERF/ETR	0	0	0	0	0	0	50	100	200	100	50	0	0	0	0	0	0	0	500
HFNS	0	0	15	30	40	40	25	0	0	0	0	0	0	0	0	0	0	0	150
HTTF	0	0	0	0	6	9	0	0	0	6	9	0	0	0	0	0	0	0	30
TF	0	0	0	5	10	20	10	5	0	0	0	0	0	0	0	0	0	0	50
B&S	0	0	0	5	10	20	10	5	0	0	0	0	0	0	0	0	0	0	50
RTNS	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INS	0	15	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
PMCTF	0	0	0	0	3	5	0	0	0	3	4	0	0	0	0	0	0	0	15
VTF	0	0	0	0	3	5	0	0	0	3	4	0	0	0	0	0	0	0	15
SMTF	0	0	0	0	10	10	10	0	0	0	0	0	0	0	0	0	0	0	30
Eng. Test. Fac. ...	0	0	0	10	20	20	20	30	30	20	20	20	10	0	0	0	0	0	200
ALT. CONC. PACE	0	0	20	50	90	150	90	40	80	200	160	200	160	200	320	160	80	0	2000
LHX																			
MX	0	0	20	50	30	0	0	0	0	0	0	0	0	0	0	0	0	0	100
LSS	0	0	0	0	20	50	30	0	0	0	0	0	0	0	0	0	0	0	100
#3	0	0	0	0	20	50	30	0	0	0	0	0	0	0	0	0	0	0	100
#4	0	0	0	0	20	50	30	0	0	0	0	0	0	0	0	0	0	0	100
M-PEPR	0	0	0	0	0	0	0	40	80	160	80	40	0	0	0	0	0	0	400
A-PEPR	0	0	0	0	0	0	0	0	0	40	80	160	80	40	0	0	0	0	400
EPR	0	0	0	0	0	0	0	0	0	0	0	0	80	160	320	160	80	0	800
TOTAL PACE	22	98	140	135	247	394	410	275	430	512	527	400	310	380	680	520	260	60	5680
OPERATIONS	120	200	270	350	420	470	490	510	530	540	550	560	570	580	590	600	610	620	8260
EQUIPMENT	17	31	27	35	42	47	49	51	53	54	55	56	57	58	59	60	61	62	826
TOTAL PROGRAM	159	329	437	520	709	911	949	836	1013	1106	1132	1016	937	1018	1329	1180	931	742	14766

Figure VI-4 PROGRAM COSTS BY YEAR FOR LOGIC V REFERENCE OPTION ($M)

	FY76	FY77	FY78	FY79	FY80	FY81	FY82	FY83	FY84	FY85	FY86	FY87	FY88	FY89	FY90	13yr. Total FY78-90
TOKAMAK PACE	20	90	110	230	465	485	385	385	370	150	160	320	600	320	160	4140
TFTR	20	90	110	30	15	35	35	15	0	0	0	0	0	0	0	240
PEPR/ITR	0	0	0	80	180	180	80	0	0	0	0	0	0	0	0	520
EPR I	0	0	0	120	270	270	120	0	0	0	0	0	0	0	0	780
EPR II	0	0	0	0	0	0	150	370	370	150	0	0	0	0	0	1040
DEMO	0	0	0	0	0	0	0	0	0	0	160	320	600	320	160	1560
ENG. FAC. PACE	2	18	40	130	190	260	385	335	180	70	50	50	20	0	0	1710
FERF/ETR	0	0	0	0	0	100	225	225	100	0	0	0	0	0	0	650
HFNS	0	0	30	60	80	60	50	20	0	0	0	0	0	0	0	300
HTTF	0	0	0	10	10	0	0	0	10	10	0	0	0	0	0	40
TF	0	0	0	10	20	20	10	5	0	0	0	0	0	0	0	65
B&S	0	0	0	10	20	20	10	5	0	0	0	0	0	0	0	65
RTNS	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INS	0	15	10	0	0	0	0	0	0	0	0	0	0	0	0	10
PMCTF	0	0	0	5	5	0	0	0	5	5	0	0	0	0	0	20
VTF	0	0	0	5	5	0	0	0	5	5	0	0	0	0	0	20
SMTF	0	0	0	10	10	10	10	0	0	0	0	0	0	0	0	40
Eng. Test. Fac.	0	0	0	20	40	50	80	80	60	50	50	50	20	0	0	500
ALT. CONC. PACE	0	0	104	364	312	156	520	728	520	156	321	728	728	312	0	4940
LHX																
MX	0	0	52	78	0	0	0	0	0	0	0	0	0	0	0	130
LSS	0	0	52	78	0	0	0	0	0	0	0	0	0	0	0	130
#3	0	0	0	52	78	0	0	0	0	0	0	0	0	0	0	130
#4	0	0	0	52	78	0	0	0	0	0	0	0	0	0	0	130
#5	0	0	0	52	78	0	0	0	0	0	0	0	0	0	0	130
#6	0	0	0	52	78	0	0	0	0	0	0	0	0	0	0	130
M-PEPR	0	0	0	0	0	78	182	182	78	0	0	0	0	0	0	520
M-PEPR	0	0	0	0	0	78	182	182	78	0	0	0	0	0	0	520
A-PEPR	0	0	0	0	0	0	78	182	182	78	0	0	0	0	0	520
A-PEPR	0	0	0	0	0	0	78	182	182	78	0	0	0	0	0	520
EPR	0	0	0	0	0	0	0	0	0	0	156	364	364	156	0	1040
EPR	0	0	0	0	0	0	0	0	0	0	156	364	364	156	0	1040
TOTAL PACE	22	108	254	724	967	901	1290	1448	1070	376	522	1098	1348	632	160	10790
OPERATIONS	120	240	360	510	600	640	660	680	690	700	710	720	730	740	750	8490
EQUIPMENT	17	31	36	51	60	64	66	68	69	70	71	72	73	74	75	849
TOTAL PROGRAM	159	379	650	1285	1627	1605	2016	2196	1829	1146	1303	1890	2151	1446	985	20129

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The following selected list of documents provides additional substantive background to the DMFE planning activities and are representative of the kind of information available to management on a continuing basis.

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